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THE LOCAL CYGNUS COLD CLOUD AND FUTHER
CONSTRAINTS ON A LOCAL HOT BUBBLE

By

Geoffrey Robert Lentner
B.S., Purdue University, 2013

A Thesis
Submitted to the Faculty of the
College of Arts and Sciences of the University of Louisville
in Partial Fulfillment of the Requirements
for the Degree of

Master of Science
in Physics

Department of Physics and Astronomy
University of Louisville
Louisville, Kentucky

August 2015

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A Thesis Approved On

July 20, 2015

by the following Thesis Committee:

Thesis Director
James Lauroesch

Lutz Haberzettl

John Kielkopf

Ryan Gill

DEDICATION

This work is dedicated to my two beautiful boys, Henry and Charlie.

Their lives give mine meaning and motivation.

ACKNOWLEDGEMENTS

One does not simply earn an advanced degree without an innumerable quantity of assists, both in life and in academics. There have been and continue to be individuals who selflessly promote and support me in the pursuit of my interests. Though I cannot possibly acknowledge every person who influenced me in a way that inexorably lead to my current situation, I want to highlight the contributions of many people that have been instrumental.

There will have been countless minute situations and occurrences that have shaped my growing mind to prepare me for what ultimately became a passion. Despite being what were completely unguided forces, I am thankful to have been born into a world and society where I am enabled to spend my life pursuing knowledge.

Two individuals, though, who indeed had my best interests at heart and mind were my mother and father. I would like to formally express my debt and gratitude to my parents Robert William Lentner III and Jennifer Anne Wedge. I suspect my sudden and spontaneous leap into natural science was not expected when it occurred, or at least my eventual decision to apply for graduate studies. I truly believe that throughout my life my parents have supported me in my decisions and interests, whatever they may be. I have always felt and continue to feel loved and encouraged by them. They will tell me how proud they are of what I've accomplished and what I will accomplish. I want to express a heartfelt thank you, to say that through it all I always felt supported.

There is another person from my childhood that I must recognize as being import to my growth, both intellectually and in other areas. We did not necessarily see eye-to-eye at times but as we grew older I saw him as an inspiration. My brother, Aaron David Lentner, is arguably one of the most import people to have helped me get where I am at the present moment. It is literally the case that I could not have pursued science as a career without

his help and I am forever thankful for his vote of confidence in me when I needed it most.

I cannot neglect to acknowledge the love and support of my incredible wife, Whitney Leigh Lentner. She is my first and forever romance. She has been my encouragement even before I started on the path that lead to this thesis. Well into my undergraduate career I had the audacious idea to drop everything I had been working on and study physics. With all things in my life, she was the first person I came to. It was a complete upheaval and added much uncertainty to our future. She supported me then, and now. With our two beautiful boys Henry Francis Lentner and Charlie Alexander Lentner, graduate studies have been for me an especially rigorous challenge, particularly these past few months. I want to thank her for being such a caring and supportive wife and mother.

Academically, there are many individuals who contributed to my current success. There were several teaching assistants and professors who taught me both the substance of physics and what it really meant to be a scientist. In particular I want to mention two faculty from Purdue University that are directly responsible for getting me into a graduate program in physics. As a professor, Dr. Jaehyon Rhee peaked my motivation to pursue science. He provided my first research experience with nothing to go on but my passion. Without this initial spring board, I could not have ultimately joined the academic world. Also, Dr. Rebecca Lindell saw in me what at times I did not see myself. Without her support and constant confidence I would not have been accepted by a graduate school.

Here at the University of Louisville, many have given me both their support and collaboration. Chief among them is my advisor and mentor, Dr. James Lauroesch. We have made and will continue to make a great team. Both his intellect and kindness have gone unmatched. He has always taken an interest in my thoughts and ideas; in my two years in the department I have worked on many projects, even ones not related to our research into the ISM. It is often the case that graduate students are at the mercy of the advisor they find themselves working with. I can say with confidence that I could not have had a better advisor, intellectually or otherwise. Others have as well been in integral component to my experience. In particular, I want to acknowledge both the collaboration

and constructive criticism of the faculty and graduate students in the astrophysics group. Wherever my career takes me, I will maintain a resolute bridge between me and the department that gave me my start.

This research is based on spectral data retrieved from the ELODIE archive at Observatoire de Haute-Provence (OHP) (Moultaka et al., 2004) and has made use of Matplotlib, a 2D graphics package used for Python for application development, interactive scripting, and publication-quality image generation across user interfaces and operating systems (Hunter, 2007); SciPy, open source scientific tools for Python (Jones et al., 2001–); NumPy, a structure for efficient numerical computation (van der Walt et al., 2011); Astropy, a community Python package for astronomy (Astropy Collaboration et al., 2013); APLpy, an open-source plotting package for Python hosted at <http://aplpy.github.com>; and the SIMBAD database, operated at CDS, Strasbourg, France (Wenger et al., 2000).

ABSTRACT

THE LOCAL CYGNUS COLD CLOUD AND FURTHER CONSTRAINTS ON A LOCAL HOT BUBBLE

Geoffrey Robert Lentner

July 20, 2015

Recent studies of the local interstellar medium have identified regions of nearby cold neutral gas with unexpected low temperatures and high pressures well within the boundaries of the local cavity (Meyer et al., 2006). Now, a multi-wavelength study of the local Leo cold cloud (LLCC) has strengthened our understanding of this apparent conflict with the conventional view of this environment (Peek et al., 2011, Meyer et al., 2012). The soft X-ray background observed here cannot be completely accounted for by a local hot bubble model (Snowden et al., 2015).

Interstellar absorption of Na I (D2 λ 5889.591 and D1 λ 5895.924) was found towards δ Cygni (Welty et al., 1994). The present study will cover an extensive preliminary search of a 40 deg² field centered here. Using archival data from ELODIE, 41 of 284 targets have measurable interstellar absorption. Three of these occur along sight lines to stars within the local cavity and represent the identification of a new nearby cloud.

Further, the author has developed a suite of precision software tools packaged as an open source library for Python 3. This library builds on other popular modern packages for Python in astronomy and may help to accelerate the pace of investigation and discovery in spectroscopy.

TABLE OF CONTENTS

	Page
DEDICATION	iii
ACKNOWLEDGEMENTS	iv
ABSTRACT	vii
LIST OF TABLES	xii
LIST OF FIGURES	xiv

CHAPTER

1	INTRODUCTION	1
1.1	The Interstellar Medium	1
1.1.1	Background	1
1.1.2	The Local Bubble	2
1.1.3	Searching for Interstellar Clouds	4
1.2	Thesis Overview	4
1.2.1	Content	4
1.2.2	SLiPy	5
2	DATA	8
2.1	Archival Data	8
2.2	The Elodie Spectrograph	8
2.3	Acquisition Methods	9
2.4	Sorting and Data Management	13
2.4.1	The Simbad Database	13

2.4.2	Managing FITS Files	16
2.4.3	The Spectrum Datatype	17
3	CALIBRATIONS	22
3.1	Removal of Telluric Features	22
3.1.1	Description	22
3.1.2	Implementation	24
3.2	Heliocentric Velocity Corrections	28
3.2.1	Description	28
3.2.2	Implementation	29
4	MEASUREMENTS	31
4.1	Non-parametric Gaussian Kernel Regression	31
4.2	Spectral Plots	32
4.3	An Interactive Graphical User Interface	34
4.3.1	The Voigt Profile	36
4.3.2	Atomic Ions	37
4.3.3	Fitting Absorption Line Parameters	39
4.3.4	Equivalent Widths	41
4.3.5	Column Densities and the Apparent Optical Depth Method . .	46
4.4	Uncertainty Calculations	49
5	RESULTS	51
6	DISCUSSION	66
6.1	Structure and Target Selection Bias	66
6.2	The Soft X-ray Background	67
6.3	Stellar vs Interstellar	67

6.4	Future Studies	68
7	CONCLUSIONS	71
	REFERENCES	74
	APPENDICES	78
A	<i>HUBBLE SPACE TELESCOPE</i> PROPOSAL	78
B	OBSERVATIONAL METADATA	89
C	SOURCE CODE	101
C.1	.. <code>__init__</code>	102
C.2	.. Algorithms . Functions	103
C.3	.. Algorithms . KernelFit	105
C.4	.. Data . Atomic	107
C.5	.. Data . Elodie	111
C.6	.. Framework . Argument	113
C.7	.. Framework . Command	114
C.8	.. Framework . Display	115
C.9	.. Framework . Measurement	117
C.10	.. Framework . Options	118
C.11	.. SLiPy . Correlate	119
C.12	.. SLiPy . Fits	120
C.13	.. SLiPy . Montage	125
C.14	.. SLiPy . Observatory	136
C.15	.. SLiPy . Plot	146
C.16	.. SLiPy . Profile	151
C.17	.. SLiPy . Simbad	164

C.18 .. SLiPy . Telluric	168
C.19 .. SLiPy . Velocity	170
CURRICULUM VITAE	173

LIST OF TABLES

TABLE	Page
5.1 Non-OB Targets with Measurable Absorption – A	55
5.2 Non-OB Targets with Measurable Absorption – B	56
5.3 Non-OB Targets with No Absorption – A	57
5.4 Non-OB Targets with No Absorption – B	58
5.5 Non-OB Targets Inconclusive – A	59
5.6 Non-OB Targets Inconclusive – B	60
5.7 Non-OB Targets Inconclusive – C	61
5.8 Non-OB Targets Inconclusive – D	62
5.9 Non-OB Targets Inconclusive – E	63
5.10 OB Targets – A	64
5.11 OB Targets – B	65
6.1 Stars Observed in the Region of δ Cygnus using the Coudé Feed	70
B.1 Observational Metadata for Non-OB Measurable Targets – A	90
B.2 Observational Metadata for Non-OB Measurable Targets – B	91
B.3 Observational Metadata for Non-OB No Absorption Targets – A	92
B.4 Observational Metadata for Non-OB No Absorption Targets – B	93
B.5 Observational Metadata for Non-OB Inconclusive Targets – A	94
B.6 Observational Metadata for Non-OB Inconclusive Targets – B	95
B.7 Observational Metadata for Non-OB Inconclusive Targets – C	96
B.8 Observational Metadata for Non-OB Inconclusive Targets – D	97

B.9	Observational Metadata for Non-OB Inconclusive Targets – E	98
B.10	Observational Metadata for OB Targets – A	99
B.11	Observational Metadata for OB Targets – B	100

LIST OF FIGURES

FIGURE	Page
3.1 Telluric Correction - HD 192640	26
3.2 Telluric Correction - Altair	27
4.1 KernelFit1D Example	33
4.2 Example SPlot of Regulus	35
4.3 SPlot of HD 192639	42
4.4 SPlot of HD 192639 - Profile.MultiFit() A	43
4.5 SPlot of HD 192639 - Profile.MultiFit() B	44
4.6 SPlot of HD 192639 - Profile.MultiFit() C	45
5.1 Cygnus Field - All Data	52
5.2 Cygnus Field - Absorption	53
5.3 Cygnus Field - No Absorption	54
6.1 Stellar vs ISM Lines	69

CHAPTER 1

INTRODUCTION

1.1 The Interstellar Medium

1.1.1 Background

Before embarking on a study of a particular constituent of the local interstellar medium and our search for nearby cold clouds, it is instructional to begin with a brief description of what exactly the interstellar medium (ISM) refers to. Informative texts include Draine (2011), ¹ Spitzer (1978), ² and the earlier Aller et al. (1968). ³

Generally, we can regard essentially all matter and interactions in the galaxy *not of the stars* as being a constituent of the ISM, or at least contributing to it, though a more limited grouping is more useful. The Milky Way galaxy is approximately 100,000 light years (30.7 kiloparsecs) in diameter and home to on the order of a few hundred billion stars. However much mass is contained within all the stars in the galaxy, there is comparable mass in the diffuse gas between them. On average, there is approximately one atom/molecule per cubic centimeter in the ISM. This is in fact a better vacuum than most modern laboratories achieve. And yet, across the vast distances of interstellar space, this material together forms intricate structure on both small and large scales.

Both the composition and dynamics in the ISM are the subject of research, old and new. We know that the ISM is mostly hydrogen and helium (in proportions we expect

¹*Physics of the Interstellar and Intergalactic Medium*

²*Physical Processes in the Interstellar Medium*

³*Nebula and Interstellar Matter*, Stars and Stellar Systems, Vol VII

from knowledge of the stars and Big Bang nucleosynthesis), more or less $3/4$ and $1/4$ respectively. The hydrogen in our galaxy can be broken into two major components. The first of these is referred to as HII regions (though this notation is somewhat unique to astronomy) and is composed of hot, photoionized (H^+) hydrogen that surrounds young O and B type stars and is also distributed in the disk and halo. This gas is even more diffuse than described previously and lives at temperatures on the order of millions of kelvin. In contrast, large portions of the galaxy contain regions of hydrogen gas referred to as HI. This is cold (~ 10 K) neutral hydrogen. These regions trace much of the structure of our galaxy and constitute a considerable fraction of the mass of the ISM. This gas can emit a signature 21-cm line from hyperfine atomic transitions. There is so much that could be said about the rich physics played out across the galaxy – emission, absorption, extinction, gravitation, magnetic fields, electrostatics, star formation; a complete survey would include a substantial fraction of modern astrophysics.

One important component within the ISM though is the abundance and distribution of *metals*, the elements heavier than helium ($z > 2$). These elements paint a picture of the history and evolution of our galaxy. The first stars contained precious little heavier elements, relatively speaking, and in their death polluted the ISM with their enriched material. Every generation of stars that has followed continued this cycle of enrichment. These heavier elements offer tracers of particular physics. We can use absorption studies to not only understand the chemical evolution of our galaxy but to learn the local structure and dynamics in the immediate vicinity of the Sun.

1.1.2 The Local Bubble

The Local Bubble refers to a relatively evacuated region (or void) immediately surrounding the Solar System. Within the past 25-60 million years an expanding wave from supernovae explosions blew out an already low density region created by massive

stellar winds and displaced the local ISM to create large magnetized bubbles hundreds of parsecs across (Frisch, 2007). The boundaries of this cavity have been traced using several techniques including color excess, HI radio emission, etc. Generally, this void is thought to be filled with hot, diffuse, X-ray emitting gas at around 10^6 K (Snowden et al., 1998). Cool, more dense molecular clouds dot the boundaries and have been compressed to create star forming regions.

Our understanding of this local environment has taken considerable shape over the past few decades (and even just in the past few years). Recently, we have found that there are several warm ($T \sim 10^4$ K) clouds inside this cavity; and even that the Solar System itself lives in one of these warm clouds (Lallement et al., 2003). It was generally believed that there was no colder interstellar material in this Local Hot Bubble (LHB); however, one cloud originally identified by Verschuur (1969), has presented a challenge to this view for many years. Meyer et al. (2006) used observations of Na I (D2 $\lambda 5889.591$ and D1 $\lambda 5895.924$) and found cold interstellar absorption towards 23 stars behind the cloud. The distance to the closest of these stars (~ 42 parsecs) places this local Leo cold cloud (LLCC) well within the boundaries of the local cavity. Peek et al. (2011), using optical observations of the LLCC, constrains the distance to this material between 11 and 24.5 parsecs. Meyer et al. (2012) used observations from the *Hubble Space Telescope* of interstellar C I to directly measure the pressure in the cloud. The $40,000\text{--}80,000\text{ cm}^3\text{ K}$ thermal pressure found is much greater than was expected and indicates that it is not in thermal pressure equilibrium with its surrounding environment. Further, analysis of *Rosat* All Sky-Survey 1/4 keV (C-band) data (Peek et al., 2011, Snowden et al., 2015) shows only weak shadowing of X-ray flux towards the LLCC, indicating that a LHB of diffuse X-ray emitting gas cannot be the only source of the soft X-ray background radiation (SXBR).

1.1.3 Searching for Interstellar Clouds

It is difficult to make generalizations about the consequences and constraints placed on a LHB using only a single object. It is important to search for other, possibly similar, cold clouds in the vicinity of the Sun to further strengthen any conclusions drawn here. To this end, we are interested in conduct such a search. Recently, another field of astronomy has enjoyed much success and popularity – the search for extrasolar planets. Several new archives of moderate resolution spectra have become available and public access. These archives offer an opportunity for science outside the domain of radial velocity studies. This work consists of one such preliminary search for a nearby cold cloud.

Welty et al. (1994) has shown absorption of interstellar sodium towards δ Cygni. The hypothesis is now that there exists another of these cold neutral clouds in the direction of Cygnus. To investigate the possibility of placing further constraints on a Local Hot Bubble, an extensive search of a 40 degree square field centered here consisting of 284 spectra from the ELODIE archive has yielded numerous targets for which absorption is present; the closest of these is HD 184006 at ~ 37 parsecs.

1.2 Thesis Overview

1.2.1 Content

Each major component of this study is discussed in the following chapters, largely in procedural order. All the data used here was retrieved from the ELODIE archive. In Chapter 2, I discuss the exhaustive procedures necessary to acquire *all* relevant spectra to the present work. Every spectrum needed to be calibrated, including the removal of telluric absorption lines and performing heliocentric velocity corrections. These steps in and of themselves (considering the quantity of data) in addition to some measure of quality assurance were essentially the motivation for creating a new library of precision

software tools in a modern language and style (to be discussed). I cover these steps in Chapter 3. Further, the actual practice of fitting absorption profiles and extracting accurate measurements with appropriate uncertainties necessitated the development of an interacting, flexible fitting routine. The details of this routine as well as numerical and visual representations of the results of this work are provided in Chapters 4 and 5, respectively. In Chapter 6, I discuss the relevance of these results to the Local Hot Bubble model and our understanding of the soft X-ray background (SXRb). There is still much work to do in this area, specifically as it relates to the local Cygnus cold cloud (hereafter LCCC); A recent *Hubble Space Telescope* proposal is attached in Appendix A (the author is a co-investigator on the proposal). Further, I am publishing all the relevant metadata for all of the observations used in this study. This includes the file indices for accessing the data from the archive as well as the date and time of observation, the exposure time, and the signal-to-noise ratio. This metadata is provided in Appendix B in Tables B.1 - B.11. The tables in Chapter 5 and Appendix B that correspond to targets with measured interstellar Na I absorption are annotated with index numbers that label markers in Figures 5.2 and 5.3. Last, in Appendix C the full source code for the entire library is included for completion (with a few exceptions). This code is up-to-date as of August 10, 2015. Though, most of the code is provided, some auxiliary components have been neglected for reasons of practicality.

1.2.2 SLiPy

We are interested in continuing to identify other cold clouds; therefore, the ELODIE archive has been parsed and retrieved for every unique stellar target - one file with the highest signal to noise. This constitutes 5,296 targets (if we restrict ourselves to only HD, HR, GC, GJ, and BD catalogues). There are 284 targets within 20° of δ Cygni (the field of interest). With this many data elements, it is important to not only be consistent,

but to be efficient. Modern astronomy is headed in the direction of so called *Big Data* and it is becoming more critical for astronomers to develop new technical and software skills and strategies to meet this demand. Here, this quantity of spectra is at the limit for what is possible to analyze iteratively and with consistent quality. **SLiPy** (the Spectroscopy and astrophysics Library for Python 3) was created to accelerate my work in managing, analyzing, visualizing, and extracting measurements from spectra. It is open source (under the GNU General Public License, version 3) and is free to download from its website.

The focus of this research has been on the science; however, the reality is that the bulk of the work done here has been related to data management. We not only need to do good science but we need to do it efficiently and consistently. One of the core components of science is reproducibility. The idea behind creating much of this software has been that if it is at all possible to automate a particular procedure, the quality and efficiency of the analysis increases. Further, later work can much more easily confirm or reject these and other results with confidence because the process for making or failing to make a detection is reproducible.

In an effort to simultaneously lay bear a census of my research and document the syntax of using this library (SLiPy) I will provide code snippets along the way. The alternative would be to provide another appendix of documentation and usage details that would be referenced throughout. In-text examples however are more easily comprehensible. I will necessarily assume that the reader is familiar with the Python language to the extent that basic concepts will not be explained here. In keeping with the syntax style of packages/modules/functions/methods in Python, all of these will be referenced using bold face type. For example, **Algorithms.Functions.Lorentzian()** is referencing the Lorentzian *function* inside the Functions *module* contained within the Algorithms *sub-package* of the SLiPy package. Leading punctuation will be used to indicate a function that is a *method* for a *class* (e.g., **.resample()** is a method of the

Spectrum class). Also, the name of explicit arguments to functions will be given via italics. For example, *filepath* and *keyword* are arguments to the **Fits.Header()** function. Last, the snippets will at times compound sequentially. That is, previous variables and imports will not be reproduced in every snippet. Further, the *representation* of the result on the final line of the snippet may be printed immediately below it. For example:

```
1 from slipy import Simbad
2
3 # retrieve the right ascension and declination from SIMBAD
4 ra, dec = Simbad.Position("Alf Lyr")
```

[<Quantity 279.23473479 deg>, <Quantity 38.78368896 deg>]

In the above code snippet, the numerical output below the horizontal line is the result of issuing `[ra, dec]` at the interpreter.

CHAPTER 2

DATA

2.1 Archival Data

The recent growth in the study and search for extrasolar planets has produced several spectral archives, much of which is public access (i.e., no longer proprietary). These archives offer a number of opportunities to do good science outside the domain of extrasolar planets. This study is one such opportunity. We have an interest in searching both the Keck HIRES (Vogt et al., 1994) and ELODIE (Baranne et al., 1996) archives for absorption features indicative of local interstellar clouds. The present study principally relies on the ELODIE archive, as the data products offered are already reduced and ready for investigation. The following sections outline the use of this archive. Future work will include the automated reduction and investigation of the Keck HIRES data.

2.2 The Elodie Spectrograph

This study is based on data retrieved from the ELODIE archive. ELODIE is a fibre-fed, cross-dispersed echelle spectrograph that was mounted ¹ at the 1.93 meter telescope at the Observatoire de Haute-Provence, France (Baranne et al., 1996, Moulaka et al., 2004, Prugniel et al., 2007). Its design purpose was to provide high accuracy radial velocity measurements (needed to search for brown-dwarfs and giant planets around

¹The spectrograph was replaced by the SOPHIE (Spectrographe pour l’Observation des Phénomènes des Intérieurs stellaires et des Exoplanètes) echelle spectrograph at the 1.93 meter telescope in 2006 (Bouchy and Sophie Team, 2006).

nearby stars) and has resolution 42000.²

The ELODIE archive is an online repository of all the data taken by the spectrograph. The database contains 35, 517 spectra.³ Users can access content via an intuitive web interface that allows searching for specific targets, by position, as well as some advanced search options. The search results provide a list of names of targets resolved by the archive with a preview option and a customization tool that allows for some pipeline processes before downloading. Among these is the ability to resample the spectrum (e.g., 5850-5950 Å at 0.01 Å pixel⁻¹) and to perform continuum normalization. The high accuracy radial velocity spectra in addition to the already reduced data products with further pipeline options made ELODIE an attractive option for this research and was the reason the decision was made to rely on it.

2.3 Acquisition Methods

In addition to the web interface, the ELODIE archive can be accessed directly using url scripting. For example:

```
http://atlas.obs-hp.fr/elodie/E.cgi?&c=i&o=elodie:20031001/0016  
&z=wrs|fca[1,nor]|wrs[1,5850,5950,0.01]&a=mime:application/x-fits
```

The above url has several components to it. First, 20031001/0016 is the index of a particular file in the archive (like those listed in Tables B.1 - B.11 in Appendix B). Second, the z=wrs|fca[1,nor]|wrs[1,5850,5950,0.01] segment is a pipeline command. fca[1,nor] says to perform the continuum normalization. wrs[1,5850,5950,0.01] is a wavelength resampling command; in this case we have requested to resample as in the example used previously from 5850 - 5950 Å at 0.01 Å pixel⁻¹.

²In astronomy, resolution is defined as $R = \lambda/\Delta\lambda$.

³Previously, the archive contained around 30, 600 spectra and only about half were public access. In the past few months however all spectra have been made public.

Previous work has identified an interstellar Na I D1 component ⁴ towards δ Cygni at a distance of 51 pc within the edge of the Local Bubble (Lallement et al., 2003, Welty et al., 1994). As such, we were interested in searching a field centered here to identify whether there was a large interstellar cloud in this vicinity. A 20 degree radius (or more precisely, everything with a right ascension and declination within 20 degrees of δ Cygni) provided ample sampling of the area. The difficulty arises when trying to browse such extensive search results manually to decide which spectra are best and to only select one for a unique stellar target. To this end, the *entire* archive was accessed to the extent that by giving the positional search form the whole sky, every single file in the archive was returned in the results. This text was exported and used to construct an ascii catalogue of the entire archive containing a listing of all files. These files are organized according to the identifier they belong to. Information also listed is the signal-to-noise ratio for the spectrum reported by the archive. With this information we can use scripting techniques to comprehend the archive using any criteria of interested. How exactly this is done is covered in the next section.

After deciding what spectra (the indices of the spectra we want) to download, the actual process of downloading them has been incorporated into SLiPy. It is quite useful to have a piece of software be able to access data on your behalf in an intuitive way via a standardized API ⁵. Within the SLiPy package, there is now a dedicated **Data** sub-package with a few functioning data management products. One of these is the **Elodie** module (see Appendix C.5 for the source). In the future, the goal is to incorporate many other modules for accessing data from astronomical archives.

The **Elodie.Archive** is an object that once instantiated reads in the raw ascii catalog mentioned previously (from `../Data/Archives/Elodie.csv` by default) and parses the

⁴ $W_\lambda = 20.2 \text{ m}\text{\AA}$, $v_\odot = -18.54 \text{ km s}^{-1}$, $N = 29.6 \cdot 10^{10} \text{ cm}^{-2}$, $b = 0.42 \text{ km s}^{-1}$. (Welty et al., 1994)

⁵Wolfram's Mathematica © for example is a very sophisticated language that has built in data accessor methods.

data into a set of two Python *dictionaries*, **.files** and **.data**. These are indexed by unique target names. The **.data** member has a list of pairs consisting of the name of the file and the signal to noise for that spectrum. **.files** contains the reduced archive and by default consists only of HD, BD, HR, GC, and GJ objects,⁶ choosing the file pertaining to the spectra with the highest signal-to-noise ratio available.

```

5 from slipy.Data import Elodie
6
7 archive = Elodie.Archive()
8
9 "HD187642" in archive.files # returns True (Altair)
10 "HD045348" in archive.files # returns False (Canopus)
11
12 altair = archive.data["HD187642"]

```

```

[['elodie:19980702/0024', 206],
 ['elodie:19960902/0012', 239],
 ['elodie:20031001/0017', 228],
 ['elodie:20031001/0016', 280],
 ['elodie:20031001/0018', 245],
 ['elodie:20031001/0014', 180],
 ['elodie:20031001/0015', 201]]

```

Also included within the module are the **Elodie.Script()** and **Elodie.Download()** functions. **Elodie.Script()** was not really intended as an end-user product, but is a convenient helper-function to **Elodie.Download()**. It merely takes the properly formatted file index of a spectrum from the archive (and optionally a pipeline command-string) and constructs the necessary url script to download that file to your machine.

Elodie.Download() is a high-level function that actually retrieves the file for you. The idea here is that in the future the **SLiPy.Data** sub-package will be expanded to provide access to numerous archives, surveys, and data sets - all with similar accessor methods. So while the content of the different archive members will invariably be distinct, the *methods* for retrieving that data from within the software will be uniform. For this study, the **Elodie** module allowed me to concisely crawl and sort the archive using **Simbad** (a module

⁶Henry Draper, Bonner Durchmusterung, Bright Star (though abbreviated using the name of its predecessor the Harvard Revised Photometry Catalogue), General Catalogue, and Gliese-Jahreiss (respectively) are all the names of stellar catalogues.

discussed in the following section). Ultimately, I was able to automatically identify the 5, 296 unique stellar targets ⁷ and retrieve the corresponding spectrum with the highest signal-to-noise ratio available. ⁸

Elodie.Download() takes an arbitrary number of file names (in the format represented above) and actually downloads them to your machine for you. There are a few options as well. First, both the continuum normalization and wavelength resampling pipeline options are accessible. By default, *normalize* is set to True and *resample* is left unspecified (leaving the spectrum at the original wavelength calibration). To specify a desired resampling, pass a tuple of length three to *resample* (starting wavelength, ending wavelength, and resolution in angstroms and angstroms per pixel respectively). Further, by default the FITS files will be downloaded to your current working directory. To specify an alternative location, give the desired relative path as *outpath*. Also, all files downloaded will have names matching the pattern, “elodie-yyyymmdd-nnnn.fits”. If you provide a list of file *names* equal in length to the number of files requested, the downloaded FITS files will be given these alternative names instead. Last, this can be a non-trivial length of time needed to download a data set. By default *verbose* is set to True and a progress bar is displayed while the files are being downloaded and an estimated time of completion is given.

```

13 # the "data" has the actual file name as the first "entry" in each pair
14 regulus = [ entry[0] for entry in archive.files["HD087901A"] ]
15
16 Elodie.Download( *regulus, resample=(5850, 5950, 0.01),
17                outpath="./Data/")

```

```

Downloading 6 files from Elodie ...
[=====>] 50.00 % ETC: 2015-06-18 @ 14:24

```

⁷Sometimes in the ELODIE archive there are stars which are the same but are labeled with an appended “A” or “B” (not necessarily corresponding to binary systems). As such, about a dozen of the targets from the 284 identified in the Cygnus field are actually duplicates. This has been handled appropriately.

⁸While not necessarily representing the absolute best piece of data, using the S/N as a benchmark for automatically sorting the data quality is useful. In a few instances, despite having the highest S/N, spectra from the archive were of too poor quality to provide any meaningful results.

In the above code snippet the `*regulus` syntax means to expand the list as if we had typed them in manually. Here, we would have downloaded the six files from the Elodie archive for Regulus ⁹ to a “Data” directory within the current working directory.

2.4 Sorting and Data Management

As alluded to previously, there are a number of modules developed for SLiPy that provide tools for handling and managing astronomical data. Among these (to be discussed here) are the **Simbad**, **Fits**, and **Spectrum** modules.

2.4.1 The Simbad Database

The **Simbad** (see Appendix C.17) module allows the user to query the SIMBAD astronomical database from *inside* Python or shell commands and scripts. It’s four current major functions **Position**, **Distance**, **Sptype**, and **IDList** return real variables with appropriate types ready for use. While the module’s implementation was remarkably strait forward, its impact for this research was nearly unmatched in terms of what it afforded to me in my ability to quickly and confidently put data elements into context and organize them. A full 85% of the content provided in Tables 5.1 - 5.11 and B.1 - B.11 were auto generated using these functions.

The approach taken is similar to the accessor method from the **Elodie** module. Here, a **Simbad.Query** class uses the **Simbad.Script()** and **Simbad.URLEncode()** helper functions to put together a url script recognized by the SIMBAD astronomical database. When querying the database, a file is returned with some standard retrieval information and statistics along with the results of your query. The format for this file is quite standardized and allowed for a common query object that is instantiated by each of

⁹Unfortunately, as described previously, some of the targets have an “A” appended to them. If you think a star is in the archive and it comes up false, try adding an “A”.

the specialized functions. That is, the **Simbad.Distance()**, **Simbad.Position()**, **Simbad.Sptype()**, and **Simbad.IDList()** functions are wrappers to creating the query object. They each take a string value specifying the identifier of the target of interest. Each function then creates the query object with a specialized parameter string ¹⁰ specific to the attribute of interest and retrieves the file from SIMBAD. The final step is to extract the relevant information from the file and return the data with an appropriate type (either a string or a **Quantity** ¹¹).

The following are some example uses. The format of the identifier string is very flexible and can be literally anything that would otherwise be recognized by conducting a search *by identifier* using the online search form at *simbad.u-strasbg.fr/simbad*.

```

18 from slipy import Simbad
19
20 # distance in parsecs to Regulus
21 distance = Simbad.Distance("regulus")

```

```

<Quantity 24.313153415998055 pc>

```

```

22 # position of Messier 31
23 ra, dec = Simbad.Position("M31")

```

```

[<Quantity 10.684708 deg>, <Quantity 41.26875 deg>]

```

```

24 # the prototype for its namesake variable type
25 sptype = Simbad.Sptype("delta scuti")

```

```

'F2IIIp'

```

```

26 # search the database for alternative identifiers of the "north star"
27 idlist = Simbad.IDList("north star")

```

```

['2MASS J02314822+8915503',
 'ADS 1477 AP',
 '** STF 93A',
 'WDS J02318+8916A',
 '** WRH 39',
 'NAME Lodestar',
 'PLX 299',

```

¹⁰For example, %C00(d;C) is the code for retrieving the right ascension and declination of the target in decimal degrees.

¹¹The **Quantity** object is meant to represent a value that has some unit associated with the number. (Astropy Collaboration et al., 2013)

```

'SBC9 76',
'* 1 UMi',
'* alf UMi',
'AAVSO 0122+88',
'ADS 1477 A',
'AG+89 4',
'BD+88 8',
'CCDM J02319+8915A',
'CSI+88 8 1',
'FK5 907',
'GC 2243',
'GCRV 1037',
'GEN# +1.00008890A',
'GSC 04628-00237',
'HD 8890',
'HIC 11767',
'HIP 11767',
'HR 424',
'IDS 01226+8846 A',
'IRAS 01490+8901',
'JP11 498',
'N30 381',
'NAME NORTH STAR',
'NAME POLARIS',
'PMC 90-93 640',
'PPM 431',
'ROT 3491',
'SAO 308',
'SBC7 51',
'SKY# 3738',
'TD1 835',
'TYC 4628-237-1',
'UBV 21589',
'UBV M 8201',
'V* alf UMi',
'PLX 299.00',
'WDS J02318+8916Aa,Ab']

```

Taking the names of the available unique targets from the ELODIE archive and doing a search for their right ascension and declination I was able to restrict my list to site lines inside the 40° field of interest. Before downloading the files, I was able to again query SIMBAD on this smaller set of targets and retrieve their spectral types. Inserting the first letter of the spectral type into the path of the *names* given to **Elodie.Download()** (e.g., “/A/”) after creating the appropriate directory structure, I was able to easily organize the data by spectral type.

2.4.2 Managing FITS Files

In order to analyze these data we need to get it out of the FITS files. Many software libraries and languages have implementations for doing such. In fact, within Python the Astropy Project ¹² already has significant capabilities (Astropy Collaboration et al., 2013). The **Fits** module within SLiPy builds on the functionality provided by **astropy.io.fits**. The most significant item provided by the module is the **Fits.GetData()** function. I'll document its usage here, and in relation to it the usage of some other related functions.

Fits.GetData() can be used in two ways. First, an arbitrary number of *files* can be requested via their relative paths. Second (or in combination with the first), you can provide the name of a *toplevel* directory under which there exists some FITS files. With the first method it will simply extract the data from those listed files. With the second, either the **Fits.Find()** or the **Fits.RFind()** function will be used first to search under or recursively under the *toplevel* directory named. By default it uses **Fits.Find()** but if *recursive* is assigned True then it uses **Fits.RFind()**. Both **Fits.Find()** and **Fits.RFind()** take two optional arguments. If no arguments are given it will return a list of the relative paths to *.fits files below the current working directory. If given an argument, it is expected to be the relative path to an alternative directory (under which it will search for *.fits files). The second argument, when provided, is an alternative glob pattern to match (e.g., *.fits.gz).

```
28 # find file path names under 'Regulus' directory and import data
29 files = Fits.Find("Data/Regulus")
30 regulus = Fits.GetData(*files)
31
32 # files organized under 'Data/All/{0,B,A,F,G,K,M}' directories
33 spectra = Fits.GetData(toplevel="Data/All", recursive=True)
```

```
Importing data from 284 Fits files ...
[=====> ] 47.18 %
```

¹²The Astropy Project is a community effort to develop a single core package for Astronomy in Python and foster interoperability between Python astronomy packages (www.astropy.org).

In the above snippet, we have imported two groups of spectra. First, the six files for Regulus from the previous example are now assumed to be under the “Data/Regulus” directory. Their paths are read in and expanded in the *files* arguments to the **Fits.GetData()** function. Similarly for the remainder of the FITS files, except they are housed under subdirectories according to spectral type. The return type of this function is a Python *list* of **Spectrum** objects.

2.4.3 The Spectrum Datatype

In an effort to reduce complexity and make operations more intuitive, a new data type was created, the **Spectrum**. As of today, I argue that there does not currently exist an implementation of a 1D spectrum object for the Python language as functional and dynamic as this one. It is important to highlight this aspect of SLiPy because throughout the following chapters I will necessarily refer to the arguments of the various functions as being of type **Spectrum**.

A **Spectrum** can be created two distinct ways. The first (as done by the **Fits.GetData()** function) is to provide a *filename*. With a proper FITS file containing both the flux data and also the corresponding wavelength calibration, the **Fits.Header()** function is used to retrieve the "CRPIX1", "CRVAL1", and "CDELTA1" values from the header and construct a wavelength array equal in length to that of the flux data.¹³ Once created, the flux data and wavelength array can be accessed independently with the **.data** and **.wave** members respectively. Units are bound to the arrays via **astropy.units**.¹⁴ If the units are not specified by the *xunits* and *yunits* keyword arguments then the flux data (*yunits*) will be dimensionless and the wavelength array (*xunits*) will be in Angstroms. If

¹³Although you can request an alternative *key* to be read from the FITS files by specifying it as an argument of the same name (e.g., `Spectrum("myData.fits", crpix1="something else")`).

¹⁴While units are bound to the arrays, it is assumed unless provided by the *xunits* and *yunits* keywords that they are dimensionless.

wavecal is assigned False and no wavelength calibration is read from the header, an array of pixel values will be generated in its place. Alternatively, instead of providing a *filename* you can provide a *data* array directly. If no *wave* array is given as a second argument, a pixel array will be generated as in the previous case. If no units are bound to these arrays, they will be assigned as dimensionless.

```

34 from slipy import Spectrum
35
36 regulus = Spectrum("Data/elodie_19960502_0013.fits")

```

```

[ 1.01038098  1.01141405  1.01213932 ...,  0.9898265   0.99048185
  0.99079037]
[ 5850.    5850.01  5850.02 ...,  5949.98  5949.99  5950.   ] Angstrom

```

```

37 import numpy as np
38
39 data      = np.random.rand(4)
40 spectrum = Spectrum(data)

```

```

[ 0.91460036  0.04310631  0.92479238  0.40179515]
[ 1.  2.  3.  4.] pix

```

In addition to the benefit of simplicity in passing around data as a **Spectrum** such that it brings with it its wavelength information (plus other attributes like header information can be attached), creating such an object allows for operator overloading in a fashion that behaves like you would think a spectrum should. Addition, subtraction, multiplication, division, comparison operators, and shift operators are all defined.¹⁵ If both operands are of type **Spectrum** the operation is applied element wise, but after insuring that both are on the same wavelength domain. If the RHS spectrum is on a different wavelength domain the units will be converted to the units of the LHS if they are different and then the RHS will be resampled onto the wavelength domain of the LHS before the operation is applied. There is a very import behavior to highlight here however. You are allowed to operate one spectrum on another that is defined on a different but overlapping band. For example, if *SpectrumA* is defined on 500-600 *nm* and *SpectrumB* is

¹⁵Includes +, -, *, /, +=, -=, *=, /=, <, >, <=, >=, ==, &, ^, |, <<, >>

defined on 550-600 *nm*, the operation `SpectrumC = SpectrumA + SpectrumB` would yield a new spectrum with the wavelength domain of *SpectrumA* where all pixels that fall into the domain of *SpectrumB* are operated on. The necessary condition is that the RHS spectrum is equivalent to or entirely contained (inclusively) by the LHS.

```

41 spectrumA = Spectrum(np.array([1, 2, 3, 4, 5]))
42 spectrumB = Spectrum(np.array([2, 3, 4, 5, 6]))
43
44 spectrumA + spectrumB

```

```

[ 3.  5.  7.  9. 11.]
[ 1.  2.  3.  4.  5.] pix

```

```

41 from astropy import units as u
42
43 spectrumA.wave = spectrumB.wave.value * u.nm
44 spectrumB.wave = spectrumB.wave.value * u.nm
45
46 spectrumA * spectrumB[4:5]

```

```

[ 1.  2.  3. 20. 30.]
[ 1.  2.  3.  4.  5.] nm

```

In the immediately above code snippet, the wavelength arrays are given units of *nm* because you cannot operate on two spectra that have pixel units for wavelength arrays unless they are the same length (the alternative makes no sense!). Only the last two elements were operated on. The `[4:5]` style notation is called *slicing* and is common in several other programming languages in addition to Python. Here, its been implemented in a non-standard way. Despite how it may appear, the command does not say to select elements 4-5, but instead says to retrieve the spectrum defined between those wavelength values (assuming the same units as the wavelength array). The spectra used in this study are defined on 5850-5950 Å. So `regulus[5885:5910]` would return a new spectrum as a segment of the Regulus spectrum, all pixels contained within those two wavelength values. Additionally, a third component to the slice may optionally be given to specify a desired resolution. `regulus[5885:5910:0.1]` says to take the same segment but resample onto a new resolution (the current being 0.01 Å pixel⁻¹). This is simply *syntactic sugar* and is

equivalent to the **.resample()** function ¹⁶ (e.g., `regulus.resample(5885 * u.AA, 5910 * u.AA, 250)`, where the third argument is now the number of pixels not the resolution). Spectra can also be operated on by scalars (left hand and right hand operations).

```
47 2 * spectrumA
```

```
[ 2.  4.  6.  8. 10.]
[ 1.  2.  3.  4.  5.] nm
```

The comparison operators return a **Spectrum** object but with binary, dimensionless data. In the case where the LHS and RHS don't have identical wavelength domains, the above described behavior holds, with the exception that all pixels in the LHS spectrum that remain unaffected by the domain of the RHS are returned as *false* (i.e., "0"). This can be interesting and useful functionality to have. ¹⁷

The shift operators (`<<`, `>>`) do what you might expect. They subtract from or add to (respectively) the **.wave** array (as oppose to the **.data** array for the other operators).

```
48 spectrumA >> 2 * u.nm
```

```
[ 1.  2.  3.  4.  5.]
[ 3.  4.  5.  6.  7.] nm
```

One could then, for example, manually apply a velocity correction as follows.

```
49 from astropy.constants import c
50
51 v = 15 * u.km / u.s
52 regulus << regulus.wave * ( v / c.to(u.km / u.s) )
```

```
[ 1.01038098  1.01141405  1.01213932 ...,  0.9898265  0.99048185
 0.99079037]
[ 5849.70729751  5849.71729701  5849.72729651 ...,  5949.68229505
 5949.69229455  5949.70229405] Angstrom
```

There are several other areas of functionality provided by the **SLiPy.Data** sub-package, the **Fits** module, and the **Spectrum** object; descriptions of these features are resigned to the online documentation.

¹⁶The **.resample()** method for a spectrum performs linear interpolation by default but can employ any other method of interpolation offered by the backend function, `scipy.interpolate.interp1d()`, by passing the *kind* keyword argument (e.g., `kind = "cubic"`).

¹⁷For example, `sum( (regulus > 1).data )` would tell you how many pixels have flux data greater than one.

With these tools, along with the functions and algorithms described in the following chapters, one can more easily process larger spectral data sets with consistency.

CHAPTER 3

CALIBRATIONS

3.1 Removal of Telluric Features

3.1.1 Description

Generally speaking, spectral data of the sort used in this study will have three categories of absorption line features. First, the star (whence the photons arise) is both a source and an absorber of photons. The stellar lines will likely be the largest (greatest equivalent width). Second, one or more interstellar sources of gas and dust along the site line between the star and Earth can and will add more features to the spectrum (often *blending* with stellar features). Last, as the photons propagate through our atmosphere, specific wavelengths will be absorbed from the atomic and molecular species present therein.

One of the first pressing issues to deal with given ground based observatories is the presence of numerous absorption features in the data that arise from the Earth's atmosphere, otherwise referred to as *telluric absorption*. A popular approach taken to address this issue is to remove these lines by dividing them out using a reference or *calibration* spectrum. The idea is that by taking the spectrum of a star, ideally before and after your science target, for which there are no stellar/interstellar absorption features in the domain of interest, one can preferentially select out the features that are telluric in origin.¹ That is to say, if something is present in both spectra, by dividing one spectrum

¹The reference star of choice will be a spectral type "A" star, though sometimes a "B" star is possible.

by the other, the offending line can be removed. An import recognition here is that this only applies for spectra that have been *continuum normalized*.

Algorithmically, where there is no absorption line in the spectrum the continuum will ideally be very close if not exactly equal to 1. As such, dividing by unity proffers no change. The absorption features come down from the continuum. So in order for the division operation to work, the spectrum needs to be inverted – with the continuum at zero and signal rising above it. So we flip both spectra, perform the division, then again invert the spectrum.

Practically speaking, this is not always a clean procedure. If the two spectra are taken during significantly different times or along differing lines of site through the atmosphere (differing airmasses), the telluric features can and will have conflicting shape and saturations. The relative strength between two corresponding lines both within the same spectrum and between spectra can cause inappropriate artifacts in the resulting corrected spectrum. For this study, there were numerous stellar targets from within the ELODIE archive of early type stars from which to choose. The difficulty is in choosing the right calibration star such that there are also no interstellar features.

A complete treatment of the options and benefits of various procedures for dealing with telluric features could occupy a lengthy paper, if not several. Here, I wish to demonstrate the successful implementation of the chosen approach and comment on its effectiveness and its drawbacks. For our purposes, Regulus (α Leo, HD 87901), a B8IV star, was the best choice. While the time of observation and the position do not necessarily line up well with the targets of interest in this study, it has been demonstrated to high order that Regulus lacks an interstellar Na I D1, D2 component ² (Peek et al., 2011), an arguably more critical requirement. Because of the differing airmass (extinction levels), time of

These stars make good reference stars because they have little to no *metal* absorption features. That is to say they have little or no features other than broad Hydrogen lines in our region of interest.

²The lower limit for an interstellar component is 0.1 mÅ.

observation, and exposure between the Regulus spectra and that of the target spectra, it was necessary to modulate any spectral division algorithm to prefer calibrations that better fit the data. In other words, because the telluric features present in a spectrum of Regulus and that of a particular target could potential differ significantly, we needed to incorporate an auto-correcting feature to the algorithm that would preferentially choose a spectrum of Regulus out of many that best fit the current spectrum and choose *that* calibration.

3.1.2 Implementation

The **Telluric.Correct()** function (see Appendix C.18) takes two or more **Spectrum** arguments. The first is the spectrum to be corrected. The second argument, and any further arguments are to be *candidate* reference spectra. In this particular function, it is necessary to insure that the target spectrum occupies the same domain (not necessarily the same resolution) as the calibration spectra. One of the hallmarks of a telluric line is that it will be at zero velocity, or at least in principle it will be very near zero. As such, no velocity shift needs to be applied to the spectra before division. However, often there will be a wavelength difference of a few pixels (the extent of which depends on the resolution of the spectra). For this reason, a horizontal cross-correlation is performed to determine the optimal shift in pixels left or right on the calibration spectrum using the **Correlate.XCorr()** function (see Appendix C.11). Further, because of differing exposure times, etc., we necessarily must amplify the calibration spectra to best fit one with the other. Our goal is only to trace the continuum and telluric lines. The *best* fit from both of these correlations is quantified by minimizing the RMS (root mean square) difference between the spectra. This procedure is applied to all the provided candidate calibration spectra and the best fit is chosen to use for the division.

Options for this function include the *lag* for the wavelength correlation. This argument by default is 25 pixels but can be overridden; it is passed to **Correlate.XCorr()**

and specifies how many pixels to shift the two spectra apart in searching for the best fit. Also, a *range* can be specified for amplitude correlation. This should take the form of a *tuple* of length three and is the start, end, and number of percentages (e.g., `range=(0.5, 2.0, 151)` is the default and specifies a search between 50% and 200% of the calibration spectrum on a 1% increment). It's important to note here that only on the part of the spectra that overlap is the operation applied; so if the best shift of the chosen calibration spectrum is three pixels, than that many pixels on either side of the target spectrum will not be altered.

```

53 from slipy import Telluric
54 from slipy.Framework import Display
55 display = Display.Monitor()
56
57 # display progress while applying telluric corrections to all targets
58 for a, spectrum in enumerate(spectra):
59     display.progress(a+1, len(spectra))
60     Telluric.Correct(spectrum, *regulus, range=(0.5, 2.0, 1501))

```

```

[=====> ] 49.43 %

```

In the above code snippet we are applying the telluric correction procedure to all the spectra using the Regulus spectra from the previous examples. In this case, the density of the amplitude trials has been increased by a factor of ten, resulting in about a one second computation time for each spectrum. Figures 3.1 and 3.2 showcase the results of the **Telluric.Correct()** algorithm for two stars. HD 192640, an A2V variable star at 20^h 14^m 32.0^s +36° 48' 22.7" approximately 11° southeast of δ Cygni, is shown to have a broad stellar component and a strong interstellar component for Na I D1 and D2 in Figure 3.1. In Figure 3.2 is Altair (HD 187642), another A type star, which has no interstellar features. Suffice it to say that Altair itself could potentially be a candidate for a reference spectrum for telluric corrections. When the algorithm is given this spectrum it effectively removes all features – behavior we would expect of a successful implementation of a telluric correcting algorithm. ³

³Even better, if you give any one of the Regulus spectra as the first argument to the function you will get

Figure 3.1: The above figure showcases the **Telluric.Correct()** routine. The spectrum is of HD 192460 (b03 Cyg), an A2V variable star. As in the entire analysis for this study, Regulus (α Leo), a B8IV star, was used as the calibration spectrum. The Elodie archive has six spectra; the best fit is automatically chosen by the algorithm.

Figure 3.2: The above figure is an empirical test of the **Telluric.Correct()** routine. Here, a spectrum of Altair (HD 187642) was corrected against the same six spectra of Regulus as in Figure 3.1. As an A7V star, Altair has no absorption features in the above wavelength domain (with the exception of absorption due to Earth's atmosphere (telluric) and weak broad stellar absorption). By applying the routine to a star that might otherwise be a suitable candidate for a calibration spectrum itself, we have effectively removed every feature.

3.2 Heliocentric Velocity Corrections

3.2.1 Description

Another significant calibration to be performed is a velocity correction. The Earth is in continual motion, with both rotation and revolution. In order to un-bias the measurement of the velocity of an absorption line in spectra, we must subtract out the motion of the observer along the line of site to the target. The largest influence is from the motion of the Earth around the Sun and can cause a shift up to approximately 30 km s^{-1} . A successful algorithm for computing the velocity correction along the line of site to a target has been implemented since the 80s (Stumpff, 1980). The P. Stumpff algorithm is used in the *rvcorrect* task for IRAF. There already existed an implementation of this algorithm for Python ⁴ maintained by Dr. Sergey Koposov. ⁵ The accuracy of this is expected to be no worse than $\sim 1 \text{ m s}^{-1}$. ⁶

The algorithm computes the velocity vector of the observer due to the Earth orbiting the Sun, the motion from the Earth - Moon system, as well as the rotational velocity of the Earth. This vector is usually either with respect to the Sun, *heliocentric*, or with respect to the gravitational barycenter of the solar system, *barycentric*. The correction is the projection of this vector along the line of sight to the target. The necessary information to computer this correction is the latitude, longitude, and altitude of the observatory; the right ascension and declination of the target; and the Julian Day ⁷ at the middle of the exposure. For this study, the heliocentric velocity is used.

back a spectrum identically one at all wavelengths!

⁴Specifically for Python 2, it was necessary to modify many of the files provided in the library to conform to Python 3.

⁵Institute of Astronomy, University of Cambridge

⁶At the very least, the performance of the system put together within SLiPy was tested against the output of the *rvcorrect* task within IRAF and found to be consistent for the same input parameters.

⁷The Julian Day is a non-relative measure of the exact time an event occurs, and is defined as the count of days from 12 noon on 1 January, 4713 BC. The fraction of the current day is simply expressed as the decimals following the count.

3.2.2 Implementation

The **Velocity.HelioCorrect()** and **Velocity.BaryCorrect()** functions provide this capability. These functions provide a high level interface to the **helcorr()** function maintained by Dr. Koposov. **helcorr()** relies on a number of other modules all housed inside a library, **astrolibpy**. A modified version of this entire library is distributed with **SLiPy** (as a sub-package). The **Velocity.HelioCorrect()** and **Velocity.BaryCorrect()** functions access **helcorr()** in a more abstracted way. All the necessary arguments are condensed into two, an *observatory* and a *spectrum*. The *observatory* is an object that has the *latitude*, *longitude*, and *altitude* information. The *spectrum* argument should be of type **Spectrum** and have the right ascension, declination, and Julian Day of observation attached.⁸

In a similar design strategy as in IRAF, an **Observatory** is a thing that has attributes such as **.latitude**, **.longitude**, **.altitude**, etc. By default, there are 70 observatories defined. The 69 observatories (and attributes thereof) defined within IRAF's observatory database (usually under `noao$lib/obsdb.dat`) have been adapted to an object oriented pattern within SLiPy. The additional observatory is for the present study. It and any additional observatories can be defined as follows:

```
61 class OHP(Observatory):
62     """
63     The Observatoire de Haute-Provence, France.
64     """
65     def __init__(self):
66         self.name = 'Observatoire de Haute-Provence'
67         self.longitude = 356.286670 * u.degree # West
68         self.latitude = 43.9308334 * u.degree # North
69         self.altitude = 650 * u.meter
70         self.timezone = 1 * u.hourangle
71         self.resolution = 42000 * u.dimensionless_unscaled
```

In the above snippet “Observatory” is an abstract base class that can/should not be

⁸In Python, everything is a first class object and is dynamic. I can attach a new data member to anything by simply assigning it (e.g., `spectrum.ra = 20`).

instantiated alone. The velocity correction functions check to see if the observatory the user provided is derived from this. Units are demanded for all the arguments' attributes, such that they can be properly converted if necessary to that needed for the P. Stumpff algorithm. Below is an example usage of the **Velocity.HelioCorrect()** function. As in the **Telluric.Correct()** function, the **Spectrum** argument(s) provided are altered; nothing is returned. As mentioned previously, the metadata for each observation needs to be attached to the spectra.

```

72 from slipy import Velocity, Observatory
73
74 # attach metadata to spectra - 'files' is a list of file paths
75 for spectrum, filepath in zip(spectra, files):
76     spectrum.ra = Fits.Header(filepath, "POS1") * u.hourangle
77     spectrum.dec = Fits.Header(filepath, "POS2") * u.degree
78     spectrum.exptime = Fits.Header(filepath, "EXPTIME") * u.second
79     spectrum.mjd = Fits.Header(filepath, "MJD-OBS") * u.day
80     spectrum.jd = (spectrum.mjd + 2400000.5 * u.day +
81                   0.5 * spectrum.exptime)
82
83 # create observatory object
84 OHP = Observatory.OHP()
85
86 # calculate and apply all velocity corrections
87 Velocity.HelioCorrect(OHP, *spectra)

```

In the above snippet, the Modified Julian Day is taken from the header files because it is provided for the ELODIE files. The Julian Day at the middle of the exposure is computed using this. All data used in this study was calibrated in a similar manner.

CHAPTER 4

MEASUREMENTS

The primary purpose of this study was to identify either the definitive presents or absence of the Sodium D lines; and in their presents, measure such quantities as equivalent width, column density, velocity, and the broadening parameter. This chapter covers the several distinct components involved in doing so, including the modeling of the continuum over the line, fitting and/or deblending multiple line components, and calculating these quantities from the extracted line profile.

4.1 Non-parametric Gaussian Kernel Regression

In spectra such as these, the absorption line features come down from a background continuum level and we must model this curve over the span of the line in order to integrate over that line. The continuum will have noise however and is almost never smooth. Generally, we solve for a smooth curve through the noise and interpolate over the line gap. There are of course numerous different methods and techniques for doing both of these. Here, we have chosen to use kernel regression to both simultaneously smooth out the continuum and gain information about the error in our measurements from the noise in the data. Gaussian kernel smoothing is a popular approach and is generally applicable with a balance between performance and complexity.

SLiPy contains a sub-package, **Algorithms**, which currently houses two modules: **Functions** and **KernelFit**. It was convenient to abstract away the interface to a number of

profile functions. The Gaussian, Lorentzian, and Voigt functions are all defined (along with variants and normalized versions thereof) within the **Functions** module. Within the **KernelFit** module is the **KernelFit1D** object. Most of the functionality discussed in the rest of this chapter is defined in the **Profile** module, whose functions use the kernel fitting algorithm.

Here, we use the Nadaraya-Watson kernel regression method. Given a discrete data set of (x, y) elements with sufficient noise, we can estimate its real valued function as

$$f(x) = \frac{\sum_i k(x-x_i) y_i}{\sum_i k(x-x_i)} \quad \text{where } k(x) = A \exp\left(-\frac{x^2}{2\sigma^2}\right). \quad (4.1.1)$$

This is essentially an arithmetic mean of the data set but with weights determined by the proximity of that data point from the point in question. The Gaussian kernel, k , has a length scale (or *bandwidth*), σ . This is an important thing to understand because it must be specified by the user. When trying to model the continuum and extract the line profile from the data, the length scale must be sufficiently large as to not trace the noise yet not so large as to fail to follow the bulk shape of the curve. This is generally true of any application using kernel smoothing. For most of the ELODIE data used in this study a bandwidth of approximately 0.08 Å was optimal. An example usage of **KernelFit1D** is available in Figure 4.1

4.2 Spectral Plots

Before continuing on with this discussion, the **SPlot** (\s plät) object needs mentioning. The **Profile.Select()**, **Profile.Extract()**, **Profile.AutoFit()**, and **Profile.MultiFit()** functions each offer a graphical interface for the user to select data as a sample of the continuum and the line contained within. The arguments to these functions

Figure 4.1: The above figure showcases **KernelFit1D** in a best-usage scenario. Here, we have a synthetic data set constructed of a normalized sinc function with added both normal *white* and *red* noise. The analytical curve is shown with a thin solid red line. The bold blue dashed line is the solution using the kernel smoothing algorithm with a *bandwidth* of $\pi/32$.

are all of type **SPlot**.¹

An **SPlot**, or Spectral-Plot, is a manager class for creating and maintaining figures using **matplotlib** (Hunter, 2007). Generally, using the **matplotlib.pyplot** module allows one to plot points and curves of x-y data. The x and y limits can be set, axis labels and legends (or other text) can be set. What an **SPlot** does is to retain all the calls to the most common methods applied using the **pyplot** module and allow you to pass around figures as objects. The full documentation for this feature will not be provided here (it can be accessed online), but an example should suffice. The results of the below snippet are in Figure 4.2.

```
88 from slipy import Plot
89
90 figure = Plot.SPlot(regulus[0], label="Regulus", marker="k-")
91 figure.legend(loc="lower left")
92 figure.draw()
93 figure.save("regulus.pdf")
94
95 # create many plots and access them individually
96 figure = [ Plot.SPlot(spectrum, label=Fits.Header(filepath, "OBJECT"))
97            for spectrum, filepath in zip(spectra, files) ]
98
99 # draw the first spectrum
100 figure[0].draw()
101
102 # iterate through all the plots and choose ones of interest
103 keepers = Plot.Iterate(*figure, keep="plot")
```

4.3 An Interactive Graphical User Interface

The principle function of the **Profile** module is the **MultiFit()** routine which creates, maintains, then destroys a **FittingGUI** and then takes the measurements for all the lines extracted. The following subsections outline some of the major areas involved with this. The **FittingGUI** uses the API provided by **matplotlib** to add widgets to the **SPlot** figures. The goal here is to be able to interactively fit profiles to data with one or more components.

¹Although, they may alternatively be of type **Spectrum** for which a generic **SPlot** will be created.

Figure 4.2: The output file from the example usage of the **SPlot** object.

4.3.1 The Voigt Profile

Generally, the **FittingGUI** has been programmed to have the capacity to model Gaussian, Lorentzian, and Voigt line shapes. For absorption lines (barring some more complex scenarios such as rapid rotators, etc.) we expect to see Voigt profiles. This is the result of an intrinsic line profile well approximated by a Lorentzian² that is broadened with the convolution of one or more Gaussian profiles. The first Gaussian is physical and due to both thermal (Doppler broadening) and turbulence. The second Gaussian is due to the blurring from instrumental effects.³ Together, the Voigt profile can be expressed as (Draine, 2011)

$$\phi_{\nu}^{\text{Voigt}} \equiv \frac{1}{\sqrt{2\pi}} \int \frac{d\nu}{\sigma_v} e^{-\nu^2/2\sigma_v^2} \frac{4\gamma_{ul}}{16\pi^2 [\nu - (1 - v/c)\nu_{ul}]^2 + \gamma_{ul}^2} \quad (4.3.1)$$

where the integral is over velocity and $\nu_{ul} \equiv (E_u - E_l)/h$ crosses the transition between energy levels u and l . The width of the Lorentzian reflects the fundamental uncertainty in the finite lifetimes of the energy levels against transitions to all other levels. The intrinsic width of the absorption line is related to γ_{ul} and the Einstein coefficient A_{ul} as

$$(\Delta\nu)_{\text{FWHM}}^{\text{intr.}} = \frac{\gamma_{ul}}{2\pi} = \frac{\lambda A_{ul}}{2\pi}. \quad (4.3.2)$$

The strength of the absorption transition can also be described by the oscillator strength,

$$f_{ul} \equiv \frac{m_e c}{\pi e^2} \int \sigma_{lu}(\nu) d\nu \quad (4.3.3)$$

where the monochromatic absorption cross section $\sigma_{lu}(\nu)$ to a normalized line profile ϕ_{ν} is

²The line profile is better approximated by the Kramers-Heisenberg formula (Draine, 2011).

³Though it is not necessarily the case that an instrumental line-spread function (LSF) actually be a Gaussian, this is often sufficient.

$$\sigma_{lu}(\nu) = \frac{g_u}{g_l} \frac{c^2}{8\pi\nu_{lu}^2} A_{ul} \phi_\nu . \quad (4.3.4)$$

These quantities, A_{ul} and f_{ul} , are import to relating our Voigt line profile back to physical properties.

These are analytical expressions; the **Profile** module within SLiPy relies on the relationship between the Voigt function and the Faddeeva function (a complex complementary error function). The Voigt profile can be expressed as the real part of this function, $w(z)$, as

$$V(x; \sigma, \gamma) = \frac{\text{Re}[w(z)]}{\pi \left(\sigma \sqrt{2\pi} \right)} \text{ for } z = \frac{x + i\gamma}{\sigma \sqrt{2}} . \quad (4.3.5)$$

Within the SciPy library there is a **scipy.special** module with a numerical implementation provided for **wofz()**.⁴ The profiles fit in this study come from this approach. In reality, it is only the absorbers whose profile is Voigt in shape. The actual feature in spectra is an exponential relationship, $I_\nu = I_{0,\nu} \exp(-\tau_\nu)$. For only small absorption features, this is approximately linear. Using something called the curve of growth (Draine, 2011) one can detangle the relationship between the equivalent width and the number of absorbers in a medium. Alternatively, we will employ the so called apparent optical depth method (Savage and Sembach, 1991) for non-optically thin lines; more on this in the following sections.

4.3.2 Atomic Ions

The Na I (D1 and D2) lines have oscillator strengths 0.320 and 0.641, respectively (Morton, 2003) and transition probabilities (Einstein coefficients) $6.14 \times 10^7 \text{ s}^{-1}$ and

⁴This is essentially $\exp(-z**2)*\text{erfc}(-i*z)$. Please see the Steven G. Johnson, Faddeeva W function implementation, <http://ab-initio.mit.edu/Faddeeva>, for more details.

$6.16 \times 10^7 \text{ s}^{-1}$, respectively (Kramida et al., 2014). This relates to the **FittingGUI** in that the user provides the information on both of these quantities as a single *ion* argument. So in fitting a particular absorption line in your data, you only need to specify what *ion* you are fitting and it knows the *wavelength*, *fvalue*, and *A* (in both air and vacuum) for most ions with wavelengths long-ward of the Lyman limit.

Within the **SLiPy.Data** sub-package is an **Atomic** module that not only incorporates the entire data set from Morton (2003) but defines the **Atomic.Ion** object. For the sake of brevity, this functionality will not be documented entirely here, suffice it to say however that it's a very high level aspect of the library to not require the user to look up these values as the most recent published data is already built in to the software.⁵ A short example is presented here, and again in the later example using the **Profile.MultiFit()** function.

```

104 from slipy.Data import Atomic
105
106 # find oscillator strengths for C III ions
107 Atomic.IonSearch("C III")

```

```

[(<Quantity 977.0201 Angstrom>, 0.7570010842747638),
 (<Quantity 1908.734 Angstrom>, 1.6875419997146983e-07)]

```

```

108 # find ions within a certain region
109 Atomic.IonSearch((585*u.nm, 590*u.nm), lookup="ion")

```

```

[(<Quantity 5891.5833 Angstrom>, 'Na I'),
 (<Quantity 5895.725 Angstrom>, 'Ti I'),
 (<Quantity 5897.5581 Angstrom>, 'Na I')]

```

```

110 # declare the Na I 'D2' ion
111 D2 = Atomic.Ion("Na I", 589*u.nm, A=6.16e-7*u.second, medium="air")

```

```

Ion:      Na I
Wavelength: 588.9951 nm
fvalue:    0.6408671009122726
A:         6.16e-07 s

```

⁵While the oscillator strengths for these ions is part of the software, as of today the transition probabilities have not been built in and must be specified by the user.

4.3.3 Fitting Absorption Line Parameters

With an *ion* declared we can pass it along with an *splot*, an *observatory*,⁶ and a *bandwidth* to **Profile.MultiFit()**. The first thing that happens is you are asked to select four data points along the spectrum. This is to mark the edges of the line in addition to samples of the continuum on either side. **KernelFit1D** models the continuum and the **Profile.Extract()** routine is run. With a separated line and continuum (interpolated⁷ over the absorption line gap) you are then asked to select more data points along the line to mark the suspected peaks of one or more components.

The plot moves up in the figure and *sliders* appear for a number of parameters along with radio buttons for each line selected. Above the sliders and below the plot is a preview of the absorption line parameters for each Voigt profile that is now plotted for each component. These steps are illustrated in Figures 4.3 - 4.6. What sliders appear depends on the *function* requested (“voigt” by default) and whether or not you provide an *observatory* and an *ion*. In this context, by providing both of these, *gamma* does not appear as an alterable parameter. This is because the transition probability provided by the *ion* solely determines the expected FWHM of the intrinsic profile and the only parameter to be fit is an observed *sigma*.

The broadening parameter can be extracted from the observed *sigma* as the convolution of one Gaussian on another is simply another Gaussian with

$$\sigma_{\text{convolution}}^2 = \sigma_a^2 + \sigma_b^2 . \quad (4.3.6)$$

So the width of the thermal/turbulence Gaussian is

⁶This should be either one of the defined **Observatory** objects or something derived thereof. We pass this to **Profile.MultiFit()** with an attached **.R** (resolution) so we know the FWHM of the instrumental Gaussian profile.

⁷The default is to use natural cubic spline interpolation, though alternatives can be requested by passing the *kind* keyword argument (see **scipy.interpolate.interp1d** for details).

$$\sigma_{\text{therm}} = \sqrt{\sigma_{\text{observed}}^2 - \sigma_{\text{instrument}}^2} \quad (4.3.7)$$

where the resolution of the instrument gives the width,

$$(\Delta\lambda)_{\text{FWHM}} = \frac{\lambda}{R} \quad (4.3.8)$$

$$= 2 \sqrt{2 \ln 2} \sigma_{\text{instrument}} \quad (4.3.9)$$

and the broadening parameter is,

$$b \equiv \sqrt{2} \sigma_{\text{therm}} . \quad (4.3.10)$$

While the calculations are performed perpetually during the fitting process, a final calculation of the equivalent width and column density are performed after the fitting process is complete, attached to each returned *line* as **.W** and **.N** respectively of **Measurement** types.⁸ Also, the **.parameters** for the Voigt profile and the velocity, **.v**, and the broadening parameter, **.b**, are attached to each line.

The details behind the calculation of the equivalent width and column density is reserved for the following subsections. An example usage of the **Profile.MultiFit()** function is presented here. and Figures 4.3 - 4.6 showcase individual steps.

```

113 from slipy import Profile
114
115 # declare the Na I ions
116 D1 = Atomic.Ion("Na I", 589.5*u.nm, A=6.14e-7*u.second, medium="air")
117 D2 = Atomic.Ion("Na I", 588.9*u.nm, A=6.16e-7*u.second, medium="air")
118
119 # SPlot of HD 200120
120 figure = Plot.SPlot(spectra[31], label="HD 192639", marker="k-")
121 figure.legend(frameon=False, loc="lower right")
122
```

⁸The **Measurement** class is unique to SLiPy and is derived from a **Quantity** but has a **.name**, **.uncertainty**, and **.notes**. It can be operated on the same as a **Quantity** (in fact it decays to one afterwards). This functionality is in the works by contributors at Astropy by is not currently available there.

```

123 # call MultiFit()
124 line, continuum = Profile.MultiFit(figure, obs=Observatory.OHP(),
125     ion=D2, bandwidth=u.Angstrom/12, boost=20)

```

In the above snippet, the spectrum could have been passed directly to the function and the **SPlot** would have been created automatically. The idea here is that any **SPlot** can be customized and passed to the function and it will retain its attributes (e.g., we could have set the *marker* to “k+” and crosses would have been used for the data points and not an interpolated curve or we could have used `.overlay()` to add more than one **Spectrum** to the same figure and fit them simultaneously!). The extra keyword argument, *boost*, is an option that artificially inflates the number of pixels in order to increase the accuracy of the numerical integration.⁹ This is not performed during the fitting process (the preview does not boost the resolution) which is why the attached calculations might be slightly different than the previewed results.

4.3.4 Equivalent Widths

The equivalent width, W , of an absorption line is a good measure of the strength of a line, or power removed by the absorbers (Draine, 2011), and is measurable even in the face of lower resolution data or high thermal broadening. It can be expressed in a few different ways but generally is the width a line would have if it maintained the same integrated area but a height equal to that of the continuum level. It is most accurately calculated by numerically integrating the Voigt profile.

$$W = \int \left[1 - \frac{I(\lambda)}{I_0(\lambda)} \right] d\lambda \quad (4.3.11)$$

$$= \int \left[1 - e^{-\tau(\lambda)} \right] d\lambda \quad (4.3.12)$$

⁹The numerical integration uses the composite Simpson’s method (see `scipy.integrate.simps`). This is very accurate even at moderate resolution, but more elements gives more accurate results.

Figure 4.3: The blue supergiant HD 192639 is represented by an **SPlot** using SLiPy. Here we can see more than one interstellar Na I component. The **SPlot** itself can be passed as an argument to **Profile.MultiFit()**.

Figure 4.4: After passing the **SPlot** object from Figure 4.3 to **Profile.MultiFit()**, along with several necessary additional arguments, we are prompted to select four points along the spectrum to mark the boundaries of the line(s) and a sample of continuum on either side. The **KernelFitID** routine is used to smooth out the continuum and evaluate an RMS noise error.

Figure 4.5: After extracting the line(s) from the continuum in Figure 4.4 we select the peaks of the absorption line(s). Buttons not shown in the figure allow the user to pan and zoom on the spectrum. It is unavoidable that the continuum interpolated over the line will be below the wings. This is because the noise in the continuum is assumed to be equally distributed above and below the continuum. By smoothing out the continuum we draw a curve *through* the noise and the interpolated curve between the samples will be continuous, in the mathematical sense. The idea is that we can get the non-linear aspect of the continuum over the line even if it is too low at first. In the next step we can raise the overall continuum level using a *slider*.

Figure 4.6: The last phase of the **Profile.MultiFit()** routine creates an analytical profile (as a Voigt function by default) for each selection made. Above is a mid-session view during the fitting process. The currently selected line is represented by a bold dashed line. To select a different line, choose the corresponding radio button in the bottom right. The continuum fit in the previous step is represented by a solid red line and the blended (superposition) line is solid green. The sliders created (bottom left) depend on the *function* argument. When an *ion* and *observatory* are given with appropriate member attributes, a Voigt profile is used and it is assumed that we are in fact trying to fit absorption lines in astronomical spectra (generally, this routine can be used outside of this context). In this context the velocity, v , the broadening parameter, b , and the apparent column density, N are previewed between the sliders and the active plot. The sliders allow for a range of possible values that are reasonable for the lines marked.

where I_0 is the continuum and $\tau(\lambda)$ is the optical depth of the line,

$$\tau(\lambda) \equiv \ln [I_0(\lambda)/I(\lambda)] . \quad (4.3.13)$$

Within SLiPy, both the **Profile.EquivalentWidth()** and **Profile.ColumnDensity()** functions are extensions of the **Profile.OpticalDepth()** function. For a single, well behaved absorption line the **Profile.Extract()** function can be used alone without any fitting procedure and a *line* and *continuum* can be separated by selecting these regions from the *splot* given.

```

126 # extract line from continuum ("fig" is an SPlot)
127 line, continuum = Profile.Extract(fig, bandwidth=u.Angstrom/12)
128
129 # "spectrum" is the spectrum used in "fig" with "error" being
130 # the percent errors from counting statistics.
131 W = Profile.EquivalentWidth(line, continuum, error=spectrum.error)

```

```

Name = Equivalent Width
Value = 0.024997410090099946 Angstrom
Error = [ 0.01070082 -0.01070067] Angstrom
Notes = Measured using Profile.EquivalentWidth() from SLiPy

```

The above snippet is of HD 186155 and was measured to have an equivalent width for the D2 line of Na I of (25.0 ± 10.7) mÅ.¹⁰ Doing the same set of commands but instead selecting D1 gives us (17.7 ± 9.6) mÅ and the ratio $W_2 / W_1 \simeq 1.41$. This puts it on the flat portion of the curve of growth and the stronger line has become more optically thick. As such, using the equivalent width to infer the column density no longer is accurate.

4.3.5 Column Densities and the Apparent Optical Depth Method

The column density is essentially a measure of the total number of absorbers along a column and is usually expressed as the number of atoms cm⁻². With complementary observations, it can be used to understand the length of a cloud. In this case, given the

¹⁰This value of course depends on what is provided via a selection by the user!

distance to a star for which there is interstellar absorption from the LCCC, the cloud's leading edge is that much closer.¹¹ In the limit of optically thin gas, $\tau_0 \ll 1$ (where τ_0 is the optical depth at line center), the column density can be related to the equivalent width as (Draine, 2011)

$$N = \frac{m_e c^2}{\pi e^2} \frac{W}{f_{lu} \lambda_{lu}^2} \quad (4.3.14)$$

$$= 1.130 \times 10^{12} \text{ cm}^{-1} \frac{W}{f_{lu} \lambda_{lu}^2} . \quad (4.3.15)$$

There are several techniques for computing the column density of a line that might offer better results dependent on the circumstances. Here, I will review the essence of the so called “apparent optical depth method” as described by Savage and Sembach (1991). More directly, the *apparent* column density relates to the *apparent* optical depth as

$$N_a(\lambda) = \frac{m_e c^2}{\pi e^2 f_{lu} \lambda_{lu}^2} \tau_a(\lambda) . \quad (4.3.16)$$

The usage of the word *apparent* here embodies the understanding that with an instrumentally smeared line we are only measuring the *observed* absorption. In contrast with the equivalent width, the measure of column density is indeed sensitive to instrumental broadening.

In either case, there is not much that can be done for severely saturated lines. This was not the case for the majority of the lines of interest for Non-OB stars investigated in this study; however there were indeed absorption lines for which saturation was near complete. Saturation is when the optical depth of a line begins to approach one at line center, note that this often occurs well before an observed line shows a significant depth due to instrumental broadening. When photons propagate through the medium, as more

¹¹Not to insinuate that the LCCC necessarily has a hard edge.

are removed and scattered by the absorbers we cannot remove more photons that were there to begin with. So within the ISM, if the size or density of a cloud is sufficient, the absorption can be near complete before we even get all the way through. This scenario spells doom to inferring information about the extent of the cloud. As the stronger line (in the context of doublets again) becomes optically thick and as saturation sets in we lose the ability to make accurate measurements. In principle, for doublet lines who differ in the product $f\lambda$ by a factor of two, we expect that the stronger line will have double the equivalent width and the same column density.

So long as the saturation is only modest, we can gain significant empirical information about the extent of saturation by measuring the difference in the observed line strengths (Savage and Sembach, 1991). Integrating the column density per unit wavelength gives the combined apparent column density,

$$N_a = \frac{m_e c^2}{\pi e^2 f_{lu} \lambda_{lu}^2} \int \tau_a(\lambda) d\lambda . \quad (4.3.17)$$

The *true* column density can be estimated as

$$\log N_a^c = \log N_a^{n-1} + \Delta \log N_a^{n-1} \quad (4.3.18)$$

where $\Delta \log N_a^{n-1}$ is a correction factor determined from the relationship between $\log N_{\text{true}} - \log N_a^{n-1}$ and the difference $\log N_a^{n-1} - \log N_a^n$.¹² Given a value for this difference, we can estimate the correction based on published values (Savage and Sembach, 1991).

The **Profile.MultiFit()** function currently approximates the apparent column density during the fitting procedure using the optically thin approximation and the relationship between the column density and the equivalent width. Afterward, the more

¹² The n and $n-1$ refer to the strong and weak line respectively for the doublet.

accurate direct integration is performed using the **Profile.ColumnDensity()** function. The arguments consist of a *line* and a *continuum*, the same as for the **Profile.OpticalDepth()** and **Profile.EquivalentWidth()** functions. Here however we want to also provide a third, *ion*, argument (as described previously). Further, if we have already computed the apparent column density for the weaker of two lines of the same species, we can provide that measurement with the keyword argument *weakline* and the returned measurement will have the **.correction** and **.true** values attached. This uses the published corrections from Savage and Sembach (1991) and interpolates to estimate the correction given the calculated $\log N_a^{n-1} - \log N_a^n$.

```

133 # apparent column density of Na I D1 in HD 186155 (from previous example)
134 N = Profile.ColumnDensity(line, continuum, D1, error=spectrum.error)

```

```

Name = Column Density (Apparent)
Value = 181581935136.28503 1 / cm2
Error = [ 8.68433738e+10 -8.68433738e+10] 1 / cm2
Notes = Measured using Profile.ColumnDensity() from SLiPy

```

For only slightly saturated lines and/or not optically thin, we can now estimate the *true* column density by passing these results as the keyword argument, *weakline*, to **Profile.ColumnDensity()**.

4.4 Uncertainty Calculations

The uncertainties provided in this study were computed from both the noise in the continuum (RMS) and from counting statistics. Given a “raw” spectrum in counting units, the uncertainty in those counts goes as

$$\delta s_{\text{count}} = \sqrt{s} . \quad (4.4.1)$$

The uncertainty from these statistics is added in quadrature with those from the continuum fitting,

$$\delta s_{\text{total}} = \left[\delta s_{\text{count}}^2 + \delta s_{\text{rms}}^2 \right]^{1/2} \quad (4.4.2)$$

Within SLiPy, either both or neither of these may be provided. The **Profile.Extract()** function (so in turn also **Profile.MultiFit()**), attaches an **.rms** value in like units directly to the *continuum* returned. The measurement functions look for this member variable and can handle either absolute or percent units. The uncertainties from counting statistics may be provided via the *error* keyword argument (as demonstrated by the last two examples). These work both in isolated usage and in connection with each other (adding in quadrature).

Preparing an *error* spectrum from an original spectrum of counts might be accomplished as in the following example.

```

135 # build error spectrum from original counts
136 s      = Spectrum("/from/file.fits")
137 s.error = Spectrum(100 * u.percent * np.sqrt(s.data.value) /
138                   s.data.value, s.wave)

```

Be sure however to perform the same velocity corrections on both your spectra and corresponding *error* spectra.

CHAPTER 5

RESULTS

In this chapter I provide both numerical data and visual representations of the results of this study. Figures 5.1 - 5.3 all map the stellar targets from ELODIE over a 40° background sky centered on δ Cygni.¹ Figure 5.1 shows all the stellar targets; Figures 5.2 and 5.3 show the definitive detection of interstellar sodium or lack thereof, respectively. The numerical annotations in these latter two plots correspond directly with listings in Tables 5.1 - 5.2 and Tables 5.3 - 5.4, respectively, for Non-OB stars. O and B spectral type stars are typically at a much further distance than other stars. They typically showed multiple interstellar components from unique clouds at different velocities. Tables 5.3 - 5.11 provide a listing of the targets investigated and represent four categories: non-OB absorption, lack of absorption, and inconclusive results and then the OB targets. The tables provide the target name, the right ascension and declination (J2000) position, spectral classification, and distance (from parallax measurements). This data was retrieved directly from the SIMBAD database using the **Simbad** module from SLiPy. The author makes no claim of particular accuracy or uncertainty in these quantities and are provided by publications cited by SIMBAD.

¹The mosaic used in the background of Figures 5.1 - 5.3 was adapted from data retrieved from *sky-map.org*. Originally, the author attempted to construct the mosaics manually using the *Montage* image mosaicing software (montage.ipac.caltech.edu). A high-level wrapper to the *Montage* software was developed to facilitate the creation of large mosaics using DSS, SDSS, and 2MASS data (or user provided data). This functionality is provided within SLiPy under the **Montage** module (see Appendix C.13). Its usage is not documented here. Ultimately, there were serious issues with the state of the data retrieved from the DSS survey. *sky-map.org* has used the same data from DSS and put together a quality mosaic that has overcome many of these challenges. In the interest of efficiency, the *sky-map* data was used instead and converted to FITS format to mark the targets using APLpy (aplpy.github.io).

Figure 5.1: The above figure shows the entire 40° square field with every target star in the study represented. There are three different marker styles. The positive identification of interstellar sodium absorption is represented by a green circle. The definitive absence of absorption is given by a red triangle. The remaining data found to be inconclusive is given as a black square. δ Cygni is located in the center of the field and is marked by a filled-in green circle. The sizes of the markers are inversely proportional to the distance to that star. The largest markers show stars within the Local Cavity and the smallest markers are from 100 pc to more than 1 kpc.

Figure 5.2: The above figure includes those targets from Figure 5.1 that have been identified as containing measurable interstellar Na I absorption. The annotations for the markers correspond to the items in Tables 5.1 and 5.2. Targets 12 and 34 are marked as measurable but have since been rendered *inconclusive*.

Figure 5.3: The above figure includes those targets from Figure 5.1 that have been identified as containing definitively no interstellar Na I absorption. The annotations for the markers correspond to the items in Tables 5.3 and 5.4.

TABLE 5.1
Non-OB Targets with Measurable Absorption – A

Target ^α	Sp-Type ^β	RA ^β	Dec ^β	Dist ^β	W ^{γδ}	N ^{γϵ}	v ^{γζ}
		hrs	deg	pcs	mÅ	10 ¹⁰ cm ⁻²	km s ⁻¹
¹ HD 332329	A0	20.49	31.39	793.65	93.2 ^{+49.0} _{-2.6}	134.36 ^{+56.2} _{-4.1}	-23.0
² HD 192640	A2V	20.24	36.81	42.70	41.9 ^{+33.5} _{-0.7}	44.8 ^{+27.0} _{-0.8}	-40.0
³ HD 185732	A5	19.62	60.71	76.10	56.8 ^{+40.3} _{-1.3}	42.4 ^{+30.6} _{-1.8}	-30.7
⁴ HD 184471	A8...	19.56	32.58	507.61	8.6 ^{+8.3} _{-2.1}	4.4 ^{+4.3} _{-1.1}	-32.8
⁵ HD 191747	A3III	20.18	26.90	129.87	8.5 ^{+8.1} _{-0.6}	7.4 ^{+5.4} _{-0.6}	-32.8
^η ⁶ BD+314105	A2	20.49	31.69	...	...	...	...
⁷ HD 184875	A2V	19.58	42.41	176.68	34.5 ^{+28.5} _{-1.2}	14.8 ^{+12.9} _{-0.7}	-30.2
⁸ HD 184006	A5V	19.50	51.73	37.20	12.5 ^{+11.7} _{-0.8}	5.1 ^{+4.9} _{-0.5}	-14.9
^η ⁹ HD 182989	A8-F7	19.42	42.78	289.02	...	...	...
¹⁰ HD 190397	A0	20.03	57.65	348.43	134.8 ^{+38.0} _{-2.8}	198.1 ^{+34.8} _{-2.3}	-29.4
^η ¹¹ HD 197345	A2Ia	20.69	45.28	432.90	...	...	...
^η ¹² HD 172167	A0Va	18.62	38.78	7.68	...	...	...
^η ¹³ HD 195692	Am	20.53	25.80	87.03	...	...	...
¹⁴ HD 188854	A7p...	19.92	46.67	136.24	83.0 ^{+56.9} _{-2.2}	57.0 ^{+20.6} _{-1.1}	-31.8
¹⁵ HD 200723	F3IV	21.06	41.63	96.34	125.6 ^{+48.9} _{-1.1}	146.2 ^{+39.6} _{-0.9}	-34.8
¹⁶ HD 198343	F8	20.78	58.42	7692.31	...	...	-36.9
¹⁷ HD 173977	F2	18.75	57.09	187.62	20.2 ^{+18.1} _{-1.2}	24.5 ^{+7.1} _{-0.7}	-32.7
¹⁸ HD 186155	F5II-III	19.68	45.52	49.63	27.3 ^{+23.3} _{-0.7}	24.8 ^{+8.5} _{-0.4}	-32.1
¹⁹ BD+293448	F0p...	19.03	30.03	1388.89	86.4 ^{+43.4} _{-8.1}	86.9 ^{+23.3} _{-5.2}	-4.9
^η ²⁰ HD 194093	F8Iab	20.37	40.26	561.80	...	...	...
²¹ HD 198226	F0	20.80	27.46	456.62	35.1 ^{+28.8} _{-1.8}	23.6 ^{+9.5} _{-0.9}	-35.5
²² HD 190537	F0III	20.07	31.24	111.11	49.6 ^{+36.5} _{-1.1}	153.5 ^{+18.7} _{-0.7}	-37.5
²³ HD 335198	G0	20.77	28.26	273.97	74.3 ^{+47.4} _{-3.3}	92.5 ^{+23.7} _{-2.2}	-45.9
²⁴ HD 341233	G5	20.88	26.49	...	32.6 ^{+27.7} _{-3.4}	30.1 ^{+10.1} _{-1.7}	-40.1
²⁵ BD+344217	G9.5Ve+K3Ve	20.97	35.17	83.40	76.1 ^{+49.4} _{-3.2}	80.0 ^{+29.1} _{-2.2}	-27.3

^α Numbers correspond to annotations in Figure 5.2.

^β Retrieved from SIMBAD database (as of June 13, 2015); uncertainties not listed.

^γ Measurements and uncertainties computed with **Profile** module.

^δ Equivalent Width for Na I D2.

^ϵ *Corrected* Column Density for Na I line, see text (Savage and Sembach, 1991).

^ζ Velocity of Na I D2 line center, from 5,889.951 Å. Uncertainty is approximately 2.6 km s⁻¹.

^η Inconclusive identification.

TABLE 5.2
Non-OB Targets with Measurable Absorption – B

Target ^α	Sp-Type ^β	RA ^β	Dec ^β	Dist ^β	W ^{γδ}	N ^{γϵ}	v ^{γζ}
		hrs	deg	pcs	mÅ	10 ¹⁰ cm ⁻²	km s ⁻¹
²⁶ HD 190508	G5	20.04	53.89	61.96	89.5 ^{+47.6} _{-5.5}	190.6 ^{+28.7} _{-3.9}	-24.8
^{θ 27} BD+433754	G5V	20.88	44.12	...	209.9 ^{+41.9} _{-6.7}	...	-26.4
^{θ 28} HD 200019	G5	20.99	44.79	204.50	113.4 ^{+59.7} _{-2.4}	...	-39.8
²⁹ HD 199939	G9III:...	20.98	44.41	306.75	87.9 ^{+46.8} _{-4.2}	89.3 ^{+24.6} _{-2.8}	-38.4
³⁰ HD 199178	G5III-IV	20.90	44.39	101.32	11.5 ^{+10.8} _{-1.1}	12.9 ^{+4.0} _{-0.6}	-4.3
³¹ HD 335070	K0	20.75	29.27	57.41	53.8 ^{+39.4} _{-3.0}	34.8 ^{+13.9} _{-1.6}	-32.3
^{η 32} HD 193891	K0	20.36	32.31	89.13	126.9 ^{+49.0} _{-2.2}	170.1 ^{+37.5} _{-1.8}	-40.3
³³ HD 170527	K0	18.42	64.84	158.48	44.0 ^{+33.6} _{-0.8}	56.6 ^{+14.7} _{-0.5}	-14.0
^{η 34} HD 198149	K0IV	20.75	61.84	14.27	...	...	...
^{θ 35} BD+483149	K0	20.52	48.87	...	48.5 ^{+36.1} _{-2.0}	...	-24.9
^{θ 36} HD 332698	K0	19.81	29.41	61.20	67.8 ^{+43.6} _{-3.7}	...	-7.3
^{θ 37} HD 187372	M1III	19.79	47.91	299.40	48.5 ^{+36.0} _{-2.3}	...	-31.6
³⁸ HD 186619	M0III	19.73	41.77	174.83	62.6 ^{+42.5} _{-2.8}	175.6 ^{+22.8} _{-1.8}	-38.1
^{η 39} HD 186532	M5IIIa	19.70	55.46	316.46	...	...	...
^{η 40} HD 177808	M0III	19.08	31.74	189.75	...	...	-32.9
^{θ 41} HD 172381	M2III	18.64	30.45	270.27	118.1 ^{+37.7} _{-14.2}	...	-23.0
⁴² HD 190964	M1IIIa	20.09	51.84	219.30	87.8 ^{+47.0} _{-3.2}	233.5 ^{+29.0} _{-2.3}	-30.7
⁴³ HD 197939	M3III	20.74	56.49	336.70	123.7 ^{+37.9} _{-2.9}	175.2 ^{+32.4} _{-2.2}	-30.0

^α Numbers correspond to annotations in Figure 5.2.

^β Retrieved from SIMBAD database (as of June 13, 2015); uncertainties not listed.

^γ Measurements and uncertainties computed with **Profile** module.

^δ Equivalent Width for Na I D2.

^ϵ *Corrected* Column Density for Na I line, see text (Savage and Sembach, 1991).

^ζ Velocity of Na I D2 line center, from 5,889.951 Å. Uncertainty is approximately 2.6 km s⁻¹.

^η Inconclusive identification.

^θ Too Saturated to apply optical depth method.

TABLE 5.3
Non-OB Targets with No Absorption – A

	Target ^α	Sp-Type ^β	RA ^β	Dec ^β	Dist ^β
			<i>hrs</i>	<i>deg</i>	<i>pcs</i>
¹	HD 335238	A2	20.85	29.80	952.38
²	HD 196542	Ap...	20.61	39.10	...
³	HD 173648	Am	18.75	37.61	47.87
⁴	HD 191158	Am	20.12	36.83	88.11
⁵	HD 174567	A0Vs	18.83	31.63	278.55
⁶	HD 180583	F6Ib-II	19.27	27.93	429.18
⁷	HD 174912	F8	18.86	38.63	30.56
⁸	HD 181096	F6IV:	19.28	47.00	42.03
⁹	BD+443670	F8	21.01	45.50	...
¹⁰	HD 183361	F5	19.45	50.15	74.57
¹¹	HD 171635	F7Ib	18.54	57.05	649.35
¹²	HD 176051	F9V+K1V	18.95	32.90	14.87
¹³	HD 171485	F5	18.55	40.16	41.70
¹⁴	HD 195992	F5	20.56	33.39	62.54
¹⁵	HD 195295	F5Iab:	20.49	30.37	235.85
¹⁶	HD 185395	F3+V	19.61	50.22	18.34
¹⁷	HD 180712	F8	19.23	59.55	44.56
¹⁸	HD 195872	F8	20.52	56.89	66.31
¹⁹	HD 173700	F8	18.72	57.82	85.40
²⁰	HD 192804	F8V	20.26	31.24	76.22
²¹	HD 172323	F9V	18.59	63.70	43.65
²²	HD 198084	F8IV-V+F9IV-V	20.76	57.58	27.29
²³	HD 184960	F7V	19.57	51.24	25.11
²⁴	HD 184448	F8	19.53	50.18	50.63
²⁵	HD 186408	G1.5Vb	19.70	50.53	21.08
²⁶	HD 196850	G1V	20.64	38.64	27.16
²⁷	HD 175306	G9III_Fe-0.5	18.85	59.39	104.82
²⁸	HD 199191	GIII+...	20.89	54.52	151.06
²⁹	HD 185501	G5	19.63	33.89	31.96
³⁰	HD 191022	G0	20.09	48.57	50.33

^α Numbers correspond to annotations in Figure 5.3.

^β Retrieved from SIMBAD database (as of June 13, 2015);
uncertainties not listed.

TABLE 5.4
Non-OB Targets with No Absorption – B

Target ^α	Sp-Type ^β	RA ^β	Dec ^β	Dist ^β
		<i>hrs</i>	<i>deg</i>	<i>pcs</i>
³¹ HD 191649	G0	20.15	50.59	45.27
³² HD 185414	G0	19.60	56.98	24.11
³³ HD 187237	G2IV-V	19.80	27.87	26.24
³⁴ HD 186427	G3V	19.70	50.52	21.21
³⁵ HD 188326	G8IV _v	19.88	38.77	55.93
³⁶ HD 187462	G0IV	19.82	27.73	50.38
³⁷ HD 197310	G0	20.69	35.55	...
³⁸ HD 195988	G0	20.55	41.47	...
³⁹ HD 187123	G5	19.78	34.42	48.26
⁴⁰ HD 198483	G0V	20.83	25.77	51.23
⁴¹ HD 198809	G7III	20.87	27.10	57.80
⁴² HD 184499	G0V	19.56	33.20	31.92
⁴³ HD 188650	G1Ib-IIe...	19.91	37.00	369.00
⁴⁴ HD 176377	G1V	18.98	30.18	23.84
⁴⁵ HD 197666	G0	20.72	52.30	79.49
⁴⁶ HD 187792	G0	19.80	63.86	55.22
⁴⁷ HD 187748	G0	19.80	59.42	27.71
⁴⁸ HD 187876	G0	19.82	57.41	46.93
⁴⁹ HD 190771	G2V	20.09	38.48	18.79
⁵⁰ HD 189749	G	19.96	62.96	56.98
⁵¹ HD 170357	G1V	18.44	46.08	71.99
⁵² HD 182758	G0	19.42	31.80	61.46
⁵³ HD 181047	G8V	19.30	25.37	46.82
⁵⁴ HD 196361	G5	20.59	36.47	66.40
⁵⁵ HD 172393	G5	18.63	42.67	28.08
⁵⁶ HD 175441	G0	18.86	60.43	87.41
⁵⁷ HD 185269	G0IV	19.62	28.50	50.28
⁵⁸ HD 176670	K2.5III	19.00	32.15	338.98
⁵⁹ HD 188947	K0III	19.94	35.08	41.37
⁶⁰ HD 199870	K0IIIbCN...	20.97	44.47	79.30

^α Numbers correspond to annotations in Figure 5.3.

^β Retrieved from SIMBAD database (as of June 13, 2015);
uncertainties not listed.

TABLE 5.5
Non-OB Targets Inconclusive – A

Target	Sp-Type γ	RA γ <i>hrs</i>	Dec γ <i>deg</i>	Dist γ <i>pcs</i>
BD+293427	A5p...	18.99	29.80	...
HD 340577	A3	20.58	26.49	699.30
HD 200405	A0pSrCr	21.03	47.91	746.27
HD 191742	A7p	20.16	42.54	304.88
HD 192678	A4p	20.23	53.66	198.02
HD 195725	A7III	20.49	62.99	41.84
HD 177196	A6IV	19.02	46.93	37.44
HD 183534	A1V	19.46	52.32	107.53
BD+353616A	F0	19.44	35.71	...
HD 341037	F0	20.78	26.36	3333.33
HD 197572	F7Ib...	20.72	35.59	1538.46
HD 198726	F5Ib+A0.8V	20.86	28.25	369.00
BD+423935	F5.5Ib-G5Ib:	21.00	42.60	-2564.10
HD 238932	F5	18.74	56.78	120.92
BD+423607	F3	20.15	42.87	82.58
HD 194951	F1II	20.45	34.33	1000.00
HD 331319	F3Ib	19.82	31.45	...
HD 195069	F0V:	20.45	49.38	37.57
HD 193370	F6Ib	20.31	34.98	970.87
HD 200805	F5Ib	21.07	45.16	373.13
HD 178593	F8	19.14	25.37	61.35
HD 188307	F8	19.88	41.08	53.30
HD 187253	F8	19.77	54.64	72.41
HD 185239	F8	19.58	57.77	84.53
HD 175225	G9IVa	18.86	52.98	25.67
HD 173701	G8V	18.74	43.83	26.69
HD 177153	G0	19.03	41.49	41.48
HD 185351	G9IIIbCN...	19.61	44.69	40.83
BD+413931	G5	20.92	42.30	67.29
HD 175306	G9III_Fe-0.5	18.85	59.39	104.82

γ Retrieved from SIMBAD database (as of June 13, 2015);
uncertainties not listed.

TABLE 5.6
Non-OB Targets Inconclusive – B

Target	Sp-Type γ	RA γ <i>hrs</i>	Dec γ <i>deg</i>	Dist γ <i>pcs</i>
HD 182488	G9+V	19.39	33.22	15.76
HD 175900	G5	18.91	51.31	80.97
HD 193795	G4IV	20.35	28.11	70.67
HD 200391	G0V+G5V	21.04	27.81	52.00
HD 181655	G5V	19.33	37.33	25.39
BD+364301	G0	20.89	36.70	...
HD 179484	G5V	19.19	38.78	52.85
HD 190360	G7IV-V	20.06	29.90	15.86
HD 178911	G1V+K1V	19.15	34.60	52.33
HD 199598	G0V	20.96	26.41	31.63
HD 173605	G5	18.71	57.87	65.70
HD 190228	G5IV	20.05	28.31	61.61
HD 188326	G8IV _v	19.88	38.77	55.93
HD 187123	G5	19.78	34.42	48.26
HD 182736	G8IV	19.40	44.93	57.64
HD 171242	G0	18.53	45.01	61.92
HD 185657	G6V	19.63	49.28	140.25
HD 171008	G5	18.47	60.44	79.30
HD 193216	G5	20.28	50.28	30.77
HD 178911B	G5	19.15	34.60	42.59
HD 200102	G1Ib	21.00	45.00	1250.00
HD 190403	G5Ib-II	20.06	29.99	588.24
HD 174104	G0Ib	18.80	28.72	1315.79
HD 191010	G3Ib	20.11	25.69	518.13
HD 180161	G8V	19.20	57.67	20.02
HD 180683	G0	19.26	38.38	64.52
HD 197037	G0	20.66	42.25	32.33
HD 180502	G0IV	19.26	29.12	85.54
HD 197488	G2V	20.71	45.82	54.14
HD 175425	G0	18.89	37.99	53.53

γ Retrieved from SIMBAD database (as of June 13, 2015);
uncertainties not listed.

TABLE 5.7
Non-OB Targets Inconclusive – C

Target	Sp-Type γ	RA γ <i>hrs</i>	Dec γ <i>deg</i>	Dist γ <i>pcs</i>
HD 193215	G5	20.26	64.20	68.97
HD 172557	G5	18.61	63.36	52.63
HD 184601	G0	19.53	60.86	83.68
HD 199100	G5IV-V	20.89	36.13	57.60
HD 195987	G9V	20.55	41.90	22.05
HD 187548	G0V	19.82	28.61	45.11
HD 177780	G3V	19.07	41.00	55.01
HD 190605	G2V	20.08	26.05	44.98
HD 178911	G1V+K1V	19.15	34.60	52.33
HD 178450	G8VSB	19.13	30.25	27.96
HD 173024	G5	18.69	40.48	80.97
HD 173289	G5	18.71	44.27	93.81
HD 197140	G5	20.67	38.78	53.56
HD 197207	G5V	20.69	30.19	55.46
HD 189087	K1V	19.95	29.82	26.72
HD 234677	K4Ve+K7.5Ve	18.57	51.72	16.35
HD 197989	K0III-IV	20.77	33.97	22.29
HD 183255	K2.5V	19.44	49.47	25.01
HD 191026	K0IV	20.11	35.97	23.95
HD 338867	K0	19.81	27.29	...
HD 199956	K0	20.98	44.06	201.61
HD 334514	K0	20.56	31.47	...
HD 199546	K0	20.93	53.81	452.49
HD 189806	K2	20.01	32.95	189.75
HD 181209	K0	19.30	34.14	432.90
HD 188056	K3III	19.84	52.99	62.07
BD+333930	K0V	20.52	33.54	48.85
BD+334140	K0	21.06	34.22	...
HD 192787	K0III	20.26	33.73	97.47
HD 196134	K0III-IV	20.56	41.77	92.08

γ Retrieved from SIMBAD database (as of June 13, 2015);
uncertainties not listed.

TABLE 5.8
Non-OB Targets Inconclusive – D

Target	Sp-Type $^{\gamma}$	RA $^{\gamma}$ <i>hrs</i>	Dec $^{\gamma}$ <i>deg</i>	Dist $^{\gamma}$ <i>pcs</i>
HD 176408	K1III	18.95	57.81	84.67
HD 198550	K5V	20.84	29.38	20.99
HD 192910	K3Ib+	20.26	47.71	324.68
HD 193469	K5Ib	20.32	39.00	1492.54
HD 198794	K3Ib	20.85	48.03	232.02
HD 200560	K2.5V	21.04	45.88	19.47
HD 190470	K3V	20.07	25.79	21.95
BD+413306	K0V	19.32	41.63	35.68
BD+522815	K7-V	20.84	52.90	22.42
HD 332518	K5V	19.76	30.01	20.32
HD 331093	K0	19.71	31.74	55.07
HD 191806	K0	20.16	52.28	69.40
HD 171607	K0	18.53	61.78	46.75
HD 179094	K1IV	19.14	52.43	71.02
HD 198425	K2.5V	20.82	32.28	24.05
HD 188753	K0	19.92	41.87	46.23
BD+400883	M3.0V	21.00	40.07	15.29
HD 173739	M3.0V	18.71	59.63	3.57
GJ 0747	M3V	19.13	32.54	8.13
GJ 0809	M2.0V	20.89	62.15	7.05
HD 186686	M2-7e	19.73	48.78	-3448.28
GJ 0725	M3.0V	18.71	59.63	3.57
BD+394208	M3Iab:	20.48	39.98	1098.90
BD+364025	M4Iab	20.36	36.93	133.69
HD 182190	M1III	19.34	57.65	242.13
HD 199871	M0III	20.97	41.36	213.68
HD 186776	M4III	19.75	40.72	251.26
HD 175865	M5III	18.92	43.95	91.41
HD 175588	M4II	18.91	36.90	225.73
HD 184786	M4.5III	19.56	49.26	406.50

$^{\gamma}$ Retrieved from SIMBAD database (as of June 13, 2015);
uncertainties not listed.

TABLE 5.9
Non-OB Targets Inconclusive – E

Target	Sp-Type ^γ	RA ^γ <i>hrs</i>	Dec ^γ <i>deg</i>	Dist ^γ <i>pcs</i>
GJ 0815	M3.0V	21.00	40.07	15.29
GJ 0766	M4.5V	19.76	27.13	10.31
HD 189063	M0III	19.91	60.82	540.54
HD 178003	M0III	19.10	29.92	446.43
HD 180450	M0III	19.26	30.53	389.11
HD 179869	M3III	19.20	41.24	317.46
HD 187849	M2III	19.84	38.72	212.31
HD 190544	M1III	20.02	64.82	180.18
HD 199305	M2.0V	20.89	62.15	7.05
HD 173740	M3.5V	18.71	59.63	3.45
HD 331161 [€]	K5	19.77	32.02	13.61
HD 190163 [€]	M5.5-6.5e	20.02	50.04	401.61
HD 182917 [€]	M7IIIab+Be	19.41	50.24	242.72
GJ 0802 [€]	M5.0V	20.72	55.35	16.67

^γ Retrieved from SIMBAD database (as of June 13, 2015);
uncertainties not listed.

[€] Inconclusive because the spectrum was bad (see text).

TABLE 5.10
OB Targets – A

Target	Sp-Type $^{\beta}$	RA $^{\beta}$ <i>hrs</i>	Dec $^{\beta}$ <i>deg</i>	Dist $^{\beta}$ <i>pcs</i>	W $^{\gamma\delta}$ <i>mÅ</i>	N $^{\gamma\epsilon}$ 10^{10}cm^{-2}	v $^{\gamma\zeta}$ <i>kms⁻¹</i>
$^{\theta}\eta$ HD 188209	O9.5Iab	19.87	47.03	1098.90	$212.0^{+27.9}_{-3.0}$	...	-24.9
$^{\eta}$ HD 198820	B3III	20.87	32.85	531.91	$92.8^{+53.2}_{-1.5}$	$88.4^{+26.1}_{-1.0}$	-0.5
$^{\eta}$ HD 194335	B2IIIe	20.40	37.48	414.94	$101.6^{+46.5}_{-1.2}$	$118.5^{+28.2}_{-0.8}$	-20.8
$^{\eta}$ HD 200120	B1.5Vnne	21.00	47.52	434.78	$86.0^{+46.4}_{-1.0}$	$94.8^{+29.7}_{-0.7}$	-29.9
HD 182255	B6III	19.38	26.26	120.48	$16.6^{+15.4}_{-1.1}$	$11.6^{+4.8}_{-0.6}$	-5.7
$^{\eta}$ HD 338529	B5	19.54	26.39	137.93	$40.2^{+31.6}_{-1.9}$	$64.4^{+14.2}_{-1.1}$	-24.4
$^{\eta}$ HD 183056	B9sp...	19.44	36.32	216.92	$22.8^{+20.0}_{-0.7}$	$13.6^{+6.0}_{-0.4}$	-33.3
HD 174638	B8II-IIIep	18.83	33.36	294.99	$164.2^{+38.0}_{-2.4}$	$643.8^{+48.4}_{-3.5}$	-17.5
$^{\eta}$ HD 176437	B9III	18.98	32.69	190.11	$19.7^{+17.6}_{-2.0}$	$9.9^{+4.7}_{-1.1}$	-34.0
HD 180163	B2.5IV	19.23	39.15	425.53	$96.9^{+46.6}_{-1.6}$	$109.8^{+27.1}_{-1.1}$	-11.3
HD 192685	B3V	20.25	25.59	303.95	$27.8^{+23.7}_{-1.1}$	$14.9^{+6.9}_{-0.6}$	-31.2
HD 198183	B5V	20.79	36.49	235.85	$174.1^{+70.6}_{-3.5}$	$244.2^{+49.3}_{-2.6}$	-28.9
$^{\eta}$ BD+404124	B2Ve	20.34	41.36	79.49	$142.9^{+38.5}_{-3.1}$	$152.7^{+36.3}_{-2.4}$	-41.0
$^{\eta}$ HD 194279	B2Ia	20.39	40.76	1724.14	$120.8^{+41.5}_{-2.2}$	$222.0^{+33.2}_{-1.9}$	-39.9
$^{\eta}$ HD 172324	B9Ib	18.63	37.43	1030.93	$77.5^{+45.6}_{-1.6}$	$80.3^{+22.3}_{-1.0}$	-32.8
$^{\eta}$ BD+413731	B3n	20.40	42.30	2222.22	$131.2^{+36.9}_{-4.6}$	$513.6^{+35.0}_{-4.6}$	-38.5
$^{\theta}\eta$ HD 193322	O9V	20.30	40.73	595.24	$190.6^{+43.1}_{-3.8}$	...	-33.3
$^{\theta}\eta$ HD 195592	O9.7Ia	20.51	44.32	909.09	$38.3^{+30.8}_{-1.6}$	...	-27.5
$^{\theta}\eta$ HD 190864	O6.5III(f)	20.09	35.61	487.80	...	...	...
$^{\theta}\eta$ HD 191423	ON9IIIIn	20.14	42.61	5263.16	$239.1^{+10.6}_{-4.1}$	...	-37.2
$^{\theta}\eta$ HD 189957	O9.7III	20.02	42.01	-2702.70	$46.6^{+34.8}_{-2.6}$	...	-38.3
$^{\theta}\eta$ HD 192639	7.5Iabf	20.24	37.35	1886.79	...	...	-30.3
$^{\theta}\eta$ HD 191978	O8V	20.18	41.35	100000.00	...	...	-31.1
$^{\theta}\eta$ HD 190429	O4If+O9.5II	20.06	36.03	862.07	...	...	-43.4

$^{\beta}$ Retrieved from SIMBAD database (as of June 13, 2015); uncertainties not listed.

$^{\gamma}$ Measurements and uncertainties computed with **Profile** module.

$^{\delta}$ Equivalent Width for Na I D2.

$^{\epsilon}$ *Corrected* Column Density for Na I line, see text (Savage and Sembach, 1991).

$^{\zeta}$ Velocity of Na I D2 line center, from 5895.924 Å.

$^{\eta}$ Multiple components. Closest velocity listed.

$^{\theta}$ Too Saturated to apply optical depth method.

TABLE 5.11
OB Targets – B

Target	Sp-Type ^{β}	RA ^{β}	Dec ^{β}	Dist ^{β}	W ^{$\gamma\delta$}	N ^{$\gamma\epsilon$}	v ^{$\gamma\zeta$}
		<i>hrs</i>	<i>deg</i>	<i>pcs</i>	<i>mÅ</i>	10^{10}cm^{-2}	<i>kms</i> ⁻¹
^{$\theta\eta$} HD 199579	O6.5V	20.94	44.92	1666.67	...	...	...
^{$\theta\eta$} HD 193514	O7Ib	20.32	39.27	-925.93	...	...	...
^{$\theta\eta$} HD 190429	O4If	20.06	36.03	...	...	...	...
^{$\theta\eta$} HD 186980	O7.5III	19.77	32.12	-2631.58	...	...	...
^{$\theta\eta$} HD 193443	O9III	20.31	38.28	1086.96	...	...	...
^{$\theta\eta$} HD 191612	O8fpe	20.16	35.73	2040.82	...	...	...
^{$\theta\eta$} HD 192281	O4.5V(n)((f))	20.21	40.27	1265.82	...	...	...
^{$\theta\eta$} HD 191201	O9III+O9V	20.12	35.72	628.93	...	...	...
^{$\theta\eta$} HD 193237	B1-2_Ia-0_ep	20.30	38.03	3125.00	...	...	...
^{$\theta\eta$} HD 198478	B4Ia	20.82	46.11	714.29	...	...	...
^{$\theta\eta$} HD 228712	B0.5Ia	20.28	40.89	...	...	...	...
^{$\theta\eta$} HD 194839	B0.5Iae	20.44	41.38	1041.67	...	...	...

^{β} Retrieved from SIMBAD database (as of June 13, 2015); uncertainties not listed.

^{γ} Measurements and uncertainties computed with **Profile** module.

^{δ} Equivalent Width for Na I D2.

^{ϵ} *Corrected* Column Density for Na I line, see text (Savage and Sembach, 1991).

^{ζ} Velocity of Na I D2 line center, from 5895.924 Å.

^{η} Multiple components. Closest velocity listed.

^{θ} Too Saturated to apply optical depth method.

CHAPTER 6

DISCUSSION

6.1 Structure and Target Selection Bias

Looking at Figures 5.2 and 5.3 we can attempt to glean information about the possible structure of the LCCC. Using only the information from the positive absorption however is not appropriate because any apparent pattern in location here is primarily due to the fact that these were just the targets available from the archive (reflecting stars with potential exoplanets as studied by ELODIE) and not a uniform and/or unbiased selection pool of nearby stars. With that said, three stars of particular interest are HD 192640 (b03 Cyg, #2, 42.7 pc), HD 184006 (ι Cyg, #8, 37.2 pc), and HD 186155 (#18, 49.6 pc). These lines-of-sight show interstellar sodium absorption similar to that of δ Cyg (Welty et al., 1994) and are all within 50 parsecs, distances well inside the neutral gas “edge” of the local cavity. If we consider simultaneously the conclusions of the definitive absence of sodium in the spectra of all the stars represented in Figure 5.3, an imaginary line drawn from b03 Cyg to ι Cyg (nearly 15 degrees across the sky) is interrupted by a clear lack of interstellar absorption in the intervening gaps (particularly just south of ι Cyg). This punctuated chain of absorption indicates the possibility of a similar broken ribbon structure to that of the LLCC.

6.2 The Soft X-ray Background

As brought up in the Introduction, there is a soft X-ray background radiation (SXBR) believed to originate from the hot gas that fills the Local Bubble. Studies of the Local Leo Cold Cloud (Peek et al., 2011, Snowden et al., 2015) using the *Rosat* All Sky-Survey and have shown no shadowing effect despite the expectation that such shadowing should be present if the X-ray source were behind the cloud. Snowden et al. (2015) offers a concise synthesis of the constraints this places on a Local Hot Bubble given multi-wavelength observations of the LLCC and the current literature. Very recently, it has been shown that in fact the solar wind charge exchange (SWCX) contributes significantly to the SXBR at both 1/4 and 3/4 keV. A lengthy discussion of the SXBR and the constraints it places on a Local Hot Bubble are not offered here, but indeed the LLCC has provided a near perfect test case for studying the dynamics and content of the Local Bubble. Unfortunately, it offers only a sample of one object. Now, this preliminary study of the LCCC provides needed observations to now begin multi-wavelength observations and extend the current understanding of the complex of local interstellar clouds.

6.3 Stellar vs Interstellar

I would like to make a brief comment in regards to the interpretation rendered on stellar lines versus interstellar lines. It can at times be difficult to immediately distinguish between weak stellar absorption and a real interstellar component. For the most part, the dominant sodium lines can be readily separated given their size. However, we can be fooled into a detection without making velocity comparisons. As an example, in Figure 6.1, I have over-plotted ¹ HD 181047 on top of HD 198149. It was originally

¹Using `.overplot()` on a **SPlot** giving any other **SPlot** as an argument over plots the two. Any number of them can be given. The legend will automatically be updated provided they both have labels.

suspected that HD 198149 might have an interstellar component, given its velocity. By over-plotting a similar spectrum we can see that even though the one was of a strength and velocity that make it a potential detection for the LCCC, it appears to be a weak stellar line. It *moves* with the other stellar lines – an interstellar line would not.

6.4 Future Studies

Follow up and additional observations of Na I for sight-lines in the Cygnus field using the KPNO Coudé Feed are needed to confirm results presented here. Preliminary results from the Coudé Feed have shown absorption of interstellar Na I towards seven stars, including δ Cygni. Six of the targets overlap with those studied from the ELODIE archive. The detections here are consistent with those measured with ELODIE. This data is available in Table 6.1. A similar campaign to that pursued for the Leo cloud over the past decade could add to the weight of current evidence in regards to our understanding of the local cavity. A proposal to use the *Hubble Space Telescope* for some of these much need observations was submitted. The author is a co-inverstigator on this proposal. The full text for this is provided in Appendix A.

Figure 6.1: Often, narrow stellar lines can mimic interstellar absorption. An indication that a particular line may not be interstellar is when it not only appears in more than one spectrum of stars of the same type, but when after a velocity correction, it appears at the same shift from the larger component. In this figure, the spectra have been artificially shifted to overlay their lines for comparison. So while HD 198149 appears to have a narrow interstellar line and is at a velocity close to those for the cloud, it is more likely than not to in fact be stellar in origin. The D1 and D2 components in question are indicated by red arrows.

TABLE 6.1
Stars Observed in the Region of δ Cygnus using the Coudé Feed

Star	Spectral Type	l^{α} (deg)	b^{α} (deg)	Distance (parsecs)	Absorption
δ Cyg	B9.5IV	78.71	10.24	52	Y
HD 175824	FIII	78.65	19.56	53	Y
HD 179958	G4V	80.67	17.27	22	N
$^{\beta}$ HD 184006	A5Vn	83.61	15.44	38	N?
$^{\beta}$ HD 184960	F7V	83.46	14.59	26	N
$^{\beta}$ HD 185351	G9III	77.62	11.35	41	Y
$^{\beta}$ HD 185395	F4V	82.67	13.45	19	N
$^{\beta}$ HD 186155	F5II-III	78.72	11.07	49	Y
HD 187160	G0	78.16	9.60	43	Y
HD 192485	F5V	81.92	5.79	35	N
$^{\beta}$ HD 192640	A2V	74.45	1.17	41	Y
HD 192866	A3	81.99	5.99	343	Y

$^{\alpha}$ l and b refer to galactic coordinates.

$^{\beta}$ Observed with both ELODIE and KPNO Coudé Feed.

CHAPTER 7

CONCLUSIONS

The goal of this study was to search in the vicinity of δ Cygni for evidence of a new local interstellar cloud. Using public access archival data from ELODIE, we have indeed observed the absorption of interstellar sodium (D2 λ 5889.591 and D1 λ 5895.924) extensively in the 40 degree square field here. The suspected stellar origin of the D2 line from Lallement et al. (2003) is now in question, given the presents of so much interstellar sodium in the region, particularly HD 186155 (target #18 in Figure 5.2 and Table 5.1) in such close proximity to δ Cygni. These observations provide motivation for further investigation in the region. Our understanding of the Local Hot Bubble has been expanded by the observations and analysis of the Local Leo Cold Cloud and now the Local Cygnus Cold Cloud offers a new testbed for investigation.

In addition to the observations highlighted above, this work has made progress in other areas. First, it illustrates the potential for investigations of the interstellar medium using archival data provided by exoplanet studies. With the multitude of planetary search archives currently on line and coming in the near future, the amount of public access spectral data is growing and will facilitate “big data” absorption line studies for understanding the interstellar medium. With this comes the need for precision auto-calibration tools for larger spectral data sets. Indeed, at the moment one must still manually perform the fitting of individual lines; however, the reduction, preparation, and calibration of such data can be more quickly undertaken using the tools provided by

SLiPy. Using this framework it may be possible to create automatic fitting procedures in the future.

As a platform independent, free, and open source product it is now open for further community development and may in time be rolled into the existing dominant package for computational astronomy with Python. The **Spectrum** class, built using **numpy** arrays, is an efficient structure for manipulating and working with spectral data. The **Profile** module gives the user a fitting and measurement facility for analyzing absorption features in the same environment within which they work with spectra as numerical objects (not just relying on file systems). The automated **Telluric** and **Velocity** corrections offer quick and precise calibrations.

The **Telluric.Correct()** function merits particular emphasis here. As described in Chapter 3, the method of using reference spectra to control for telluric absorption is effective in many instances.¹ The all-in-one approach of the function offered here, to horizontally cross-correlate and vertical amplitude fit all the calibration spectra separately guarantees the best possible fit for the provided candidate reference spectra. With that, the ability to easily provide an arbitrary number of candidate reference spectra offers to automatically choose the best telluric reference out of all the candidates. In the region investigated in this study there exists a veritable forest of telluric lines. In the example control test plotted in Figure 3.2, immediately adjacent to the region shown, $\lambda \simeq 5810\text{\AA}$, the signal to noise was observed to be $\simeq 320$. The mean S/N in the same region for the six spectra of Regulus was $\simeq 310$. After the telluric correction procedure was applied, the signal to noise measured deep inside the afflicted region was $\simeq 210$. This is roughly a $\sqrt{2}$ reduction assuming the continuum would otherwise maintain a similar S/N up through $6000\text{\AA}$. Therefore, we conclude that the algorithm has retained the expected S/N for

¹Recently, *TelFit* (Gullikson et al., 2014) was developed for Python and offers a wrapper to the Line-By-Line Radiative Transfer Model (LBLRTM). This is a separate model than that offered by **Telluric.Correct()**.

combining the two spectra and the reduction is a consequence of averaging two stochastic sets of noise.

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APPENDIX A

HUBBLE SPACE TELESCOPE PROPOSAL

The Local Cygnus Cold Cloud - Testing the Hot Local Bubble

Scientific Category: ISM AND CIRCUMSTELLAR MATTER

Scientific Keywords: Dust, Galactic Structure, Interstellar And Intergalactic Medium

Instruments: STIS

Proprietary Period: 12

Proposal Size: Small

UV Initiative: Yes

Orbit Request

Prime

Parallel

Cycle 23

5

0

Abstract

There has recently been a revolution in our knowledge about the nature of clouds within the Local Bubble which is challenging our models for the content and structure of this gas. Over several decades a view had been developed of the Local Bubble as a cavity surrounding the Sun filled with hot ($\sim 10^6$ K) X-ray emitting gas that was devoid of cooler material. The recent detection of the Local Leo Cold Cloud within the bubble has upset this view, and we are now trying to understand the formation of extremely cold gas (20 K) within this cavity. In order to further understand the formation and nature of this material, we request observations of two stars behind the Local Cygnus Cold Cloud, the second such pocket of cold material discovered in the Local Bubble. We will search for pressure variations within the cloud, which are expected to arise where turbulent fragmentation in the wake of collisions of warm clouds pushes the localized overpressures above the limiting values implied by the measured velocity constraints on the colliding clouds.

J Lauroesch : The Local Cygnus Cold Cloud - Testing the Hot Local Bubble

Investigators:

	Investigator	Institution	Country
PI&	J Lauroesch	University of Louisville Research Foundation, Inc.	USA/KY
CoI	G Lentner	University of Louisville Research Foundation, Inc.	USA/KY

Number of investigators: 2
& Phase I contacts: 1

Target Summary:

Target	RA	Dec	Magnitude
HR-7444	19 34 41.2593	+42 24 45.04	V = 5.348, 1.7e-11 at 1565 Ang, 2.4e-11 at 1965 Ang, 1.8e-11 at 2365 Ang
-B03-CYG	20 14 32.0333	+36 48 22.69	V = 4.94 +/- 0.02, 3.5e-12 at 1598 Ang, 3e-11 at 2000 Ang

Observing Summary:

Target	Config Mode and Spectral Elements	Flags	Orbits
HR-7444	STIS/FUV-MAMA Spectroscopic E140H (1598)		2
	STIS/NUV-MAMA Spectroscopic E230H (2113)		
-B03-CYG	STIS/FUV-MAMA Spectroscopic E140H (1598)		3
	STIS/NUV-MAMA Spectroscopic E230H (2113)		

Total prime orbits: 5

■ Scientific Justification

Our knowledge of the interstellar medium in the immediate Solar vicinity has been undergoing a revolution over the past few years. But even as we begin to have a more complete census of the interstellar components near the Sun, we find ourselves facing new difficulties in integrating the multi-wavelength observations into a coherent whole. The limitations we face in our ability to model the interstellar medium near the Sun clearly reflect limitations in our ability to model the interstellar medium elsewhere in the Galaxy, for if we cannot understand the gas and dust near the Sun where we have all the advantages of proximity we have no hope of understanding what is going on in distant regions of the Galaxy. The physical conditions in the ambient interstellar medium surrounding the Sun also set the boundary conditions for the heliosphere, which is the edge of the Solar System (Frisch 1995).

From a combination of X-ray, UV and optical measurements of the interstellar medium a picture was developed over several decades of the interstellar environment within which the Solar System is embedded (Cox & Reynolds 1987; Frisch 1995). Observations suggested the existence of a “Local Bubble” – a low density cavity surrounded by dense neutral material lying roughly in the galactic plane filled with hot gas with a temperature of more than one million K (Snowden *et al.* 1998) that was the source of the observed diffuse soft X-ray background emission. The neutral gas boundary of this region was marked by a “wall” of dense gas at distances between approximately 65 and 250 pc of the Sun whose presence could be detected from strong Na I absorption detected in background stellar spectra of early-type stars (Sfeir *et al.* 1999; Lallement *et al.* 2003). More recently it was recognized that there were several warm ($T \sim 10,000$ K) clouds in the bubble, and that the Solar System is itself embedded in a warm interstellar cloud. It was generally thought that there was no cold interstellar gas within this region of space (Lallement *et al.* 2003).

One interstellar cloud presented a puzzle for almost 3 decades. Originally identified by Verschuur (1969) as two roughly degree scale patches of very narrow H I 21 cm emission in the constellation Leo. This region was subsequently re-observed as part of the Millennium Arecibo 21 cm absorption line survey (Heiles & Troland 2003). Coupling new observations of 21 cm absorption toward 3C 225 and 3C 237 with the Leiden-Dwingeloo 21 cm sky survey (Hartmann & Burton 1997), Heiles & Troland (2003) suggested that this cloud had a very thin, ribbon-like geometry. Motivated by these results, Meyer *et al.* (2006) obtained observations of the the interstellar Na I $\lambda 5889$, $5895\text{\AA}$ absorption lines toward 33 stars at different distances in the direction of the Leo cloud using the Kitt Peak National Observatory 0.9 m coudé feed telescope. An extremely narrow absorption component was detected at the same velocity as the narrow 21 cm absorption detected toward 3C 225 in the spectra of 23 of the stars whose sky positions place them within the outer contour of the H I 21 cm emission. The closest of these stars had distances of ~ 42 parsecs, placing this cloud well within the neutral gas ‘edge’ of the Local Bubble mapped by Lallement *et al.* (2003). While there were a number of warm, partially ionized clouds identified within the “Local Bubble” which was presumed to be full of hot gas (Redfield & Linksky 2004; 2008), this was the first indication of cold material within this region.

Peek *et al.* (2011) used optical observations of this Local Leo Cold Cloud (LLCC) to further constrain the distance to this material, placing it between 11 and 24.5 pc. Now such cold, neutral material will absorb X-ray emission, so if the soft X-rays observed around the Sun come from a pervasive hot gas filling the “Local Bubble” this cloud being well within the boundary should absorb the emission from the hot gas behind the cloud. In the direction of the LLCC the edge of the local cavity is between 100 and 150 pc away (Meyer *et al.* 2006). An analysis of *Rosat* All Sky-Survey 1/4 keV (C-band) data shows no shadowing of the X-ray flux in the direction of the LLCC, which suggests there is no diffuse, hot X-ray emitting bubble around the Sun (Peek *et al.* 2011). Instead Peek *et al.* (2011) suggested the source of the diffuse soft X-rays is charge exchange between the Solar Wind and the ambient interstellar medium (Cravens 1997; Cravens 2000; Wargelin *et al.* 2008). This is consistent with the model of Welsh & Shelton (2009), who suggested that much of the observed X-ray flux was due to Solar wind exchange. However Galeazzi *et al.* 2014 suggested that no more than 40% of the diffuse X-ray emission could come from Solar Wind charge exchange, and that the remainder must come from the surrounding interstellar medium. However these authors did not address the constraints from the LLCC. Further observations of cold clouds will place tight constraints on the location and origin of the diffuse X-rays.

Meyer *et al.* (2012) used *Hubble Space Telescope* observations of absorption by interstellar C I in the spectra stars behind this cloud to directly measure the pressure in this cloud. The pressures of 40,000–80,000 cm³K are much greater than that of the warm clouds in the Local Bubble, where Redfield & Linsky (2004) measured a mean thermal pressure to be 2300 cm³K for 50 warm, partially ionized clouds within the Local Bubble. Measurements of the foreground X-ray emission from Solar Wind charge exchange (Robertson *et al.* 2010) and the Peek *et al.* (2011) finding of weak X-ray shadowing by the LLCC have weakened the case for a higher-pressure hot Local Bubble. Although some hot gas is undoubtedly present, its thermal pressure is most likely in a range (3000–7000 cm³K) consistent with that of the warm clouds (Frisch *et al.* 2011). Thus it is clear that the LLCC is not in thermal pressure equilibrium with either the hot gas or the warm clouds in the Local Bubble. That the LLCC is significantly overpressured with respect to the Local Bubble is qualitatively consistent with predictions its anomalously low temperature is the result of a warm cloud collision (Vazquez-Semadeni *et al.* 2006; Meyer *et al.* 2006; Redfield & Linsky 2008). In their one-dimensional numerical simulations of the large-scale transonic (Mach number ~ 1) compression of colliding warm gas flows, Vazquez-Semadeni *et al.* (2006) find that a thin cold layer forms within the shocked interface. A common feature of the colliding warm flow models (Audit & Hennebelle 2005; Gazol *et al.* 2005; Heitsch *et al.* 2006; Vazquez-Semadeni *et al.* 2006) is the turbulent fragmentation of the cold interface layer into clumpy structures. Some of the simulations (Audit & Hennebelle 2005; Gazol *et al.* 2005) have shown that localized regions within these structures can reach pressures up to 10⁵ cm³K even when the collision is transonic (Hennebelle *et al.* 2007). It is quite likely that the different LLCC pressures measured are due in part to real localized pressure variations, where the turbulent fragmentation expected in the wake of such collisions pushes the localized overpressures above the limiting values implied by the measured velocity constraints on the colliding clouds.

In any case, the geometry and physical properties of such clouds provide constraints on theoretical models of their formation.

Currently there is only one published example of very cold material within the Local Bubble, the LLCC, and it is difficult to draw any significant conclusions for the general processes which lead to the formation of cold clouds from a sample of one object. Using the Kitt Peak National Observatory Coudé Feed telescope combined with archival optical and radio observations we have attempted to identify additional local cold clouds. The survey of Lallement *et al.* (2003) identified several anomalous sightlines within the Local Bubble which showed some possible interstellar Na I absorption, though it was typically somewhat below the limits representative of the ‘edge’ of the Local Bubble. One sightline that drew immediate attention was that toward δ Cyg – while it showed weak Na I absorption (an equivalent width of only ~ 20 mÅ, or about $\frac{1}{2}$ that seen toward the LLCC), it was notable for the narrowness of the absorption profile which shows hyper-fine splitting indicative of low temperatures and turbulent motions (Welty, Hobbs, & Kulkarni 1989; Lallement *et al.* 2003). Jenkins (2002) used C I observations from *HST*/GHRS to measure a pressure in this cloud of $10^3 < p/k < 10^4$ cm $^{-3}$ K, more similar to that measured in the warm clouds in the Local Bubble. Using archival Elodie spectrograph observations we were able to confirm that there was a large region of Na I absorption in this region (Figure 1). This local Cygnus cold cloud (LCCC) thus represents a second of what may be a population of such cold material in the Solar vicinity (with other candidate clouds already known).

The question we seek to answer is does any of the material in the LCCC have the same high pressure as in the LLCC? The sightlines through the LLCC have a mean pressure of 60,000 cm $^{-3}$ K Meyer *et al.* (2012), well in excess of the mean thermal pressure of 2300 cm $^{-3}$ K for the warm, partially ionized clouds in the Local Bubble (Redfield & Linsky 2004). Such excess pressures are expected in models that involve collisions of warm clouds (see, for example, Vazquez-Semadeni *et al.* 2006). Flow-driven formation of cold atomic and molecular clouds in models have shown that shocked flows of warm interstellar gas can provide a rapid formation of such clouds (Ballesteros-Paredes *et al.* 1999; Hennebelle & Péroult 1999; Koyama & Inutsuka 2000; Hartmann *et al.* 2001). While the timescales of instabilities in flow driven models of cold atomic and molecular cloud formation suggest that thermal instabilities drive their rapid formation (Heitsch, Hartmann & Burkert 2008), and provide seeds for local gravitational collapse. Since this gas is significantly over-pressured one would expect it to have a relatively short lifetime, but a population of high pressure cold clouds argues for either some form of confinement or the rapid production of such clouds in the turbulent warm ISM. The measurement of a lower pressure toward δ Cyg (Jenkins 2002) suggests the gradual equilibration of such clouds with the ambient ISM, and support the idea that such clouds can become the seeds of the cold neutral medium. Pressure and density measurements in additional sightlines in the LCCC will determine if there is any variation in the pressure across the cloud, and the detection of high pressure gas like in the LLCC will point to turbulent fragmentation expected in the models. The measurement of the H I column (inferred from the Zn II column) will enable us to use X-ray shadowing to place limits on the location and amount of hot gas in this direction.

Figure 1: Positions of stars with detected Na I absorption behind the δ Cyg Cloud from observations taken from the Elodie spectrograph archive. The point size indicates the distance to the star, with small points showing distant stars and large points indicating nearby stars. Delta Cyg is marked by a circle.

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Figure 2: Archival Na I absorption spectra toward our selected stars behind the δ Cyg Cloud taken with the Elodie spectrograph

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■ Description of the Observations

We have selected our targets from a sample of stars observed with the Kitt Peak Coudé Feed telescope or the Elodie spectrograph at OHP in the vicinity of δCyg (Figure 1). Stars with suitably bright UV flux as well as rapid rotation were identified, and their Na I checked to be sure that the LCCC was detected but also that no more distant gas was seen (see Figure 2). For some of these stars we take advantage of one of the ND slits.

We target the C I fine structure lines as well as the Zn II absorption lines. By fitting the C I ground and fine-structure features as well as the (optical) hyper-fine split Na I absorption line one can determine the cloud temperature and turbulent velocity. Then the C I features allow one to determine the pressure and density within the cloud by using the excitation balance (Jenkins & Tripp 2001). The Zn II lines serve as a proxy for H I since in the Cygnus region there is too much background gas to identify H I absorption or emission associated with the LCCC. From the observations we can determine a cloud thickness using the inferred H I column density and the volume density determined from C I. We can then infer a mass for the LCCC.

We will observe the strong 1560Å multiplet of C I we will use E140H centered at 1489Å, and we will observe Zn II 2026, 2062Å using E230H centered at 2113Å. In addition we will cover other lines including Si IV 1393, 1402Å, Si II 1526Å, P II 1532Å, Ti II 1910Å, Cr II 2056, 2062, 2066Å which will provide a measure of depletion and sample the warm/hot interstellar medium. We selected the 1560Å multiplet of C I due to the large exposure times needed to cover the 1656Å multiplet, and the lack of FUV flux in these objects preventing the use of multiplets such as 1277 or 1328Å.

For HD 184875 we used the fluxes from the TD1 satellite, which are 1.7×10^{-11} at 1565 Å, 2.4×10^{-11} at 1965Å, and 1.8×10^{-11} at 2365Å. We used the highest of these fluxes to check bright object protection, and then the lower fluxes to estimate the exposure time. This results in exposure times of 1,150 seconds for the 1489Å setting using the 0.2x0.09 slit and 900 seconds at 2113Å using the 31X0.05NDA.

For HD 192640 low resolution, large aperture IUE SWP spectra show a flux at 1656Å of 6×10^{-12} erg/cm²/s/Å, and a flux of no greater than 3×10^{-11} erg/cm²/s/Å anywhere in the 1763Å observation band. For the longer wavelength setting near 2113Å IUE low resolution, large aperture LWP observations show a flux of 3×10^{-11} erg/cm²/s/Å across the wavelength region of interest. These fluxes result in an exposure time of 5400 seconds at 1598Å using the 0.2x0.09 slit and at the 2113Å setting we use the 31X0.05NDA and have an exposure time of 715 seconds.

Estimating overheads of 6 minutes for guide acq (and 5 for re-acq), 6 minutes each for target acq and pickup, 8 minutes for 1st MAMA exposure. Thus the set-up time is a minimum of 26 minutes and we have 55 minutes of visibility for our targets. Thus HD 184875 will take a minimum of 2 orbits, and HD 192640 will take 3 orbits.

■ Special Requirements

None

■ Coordinated Observations

None

■ Justify Duplications

None

■ Past HST Usage

Programs in the last 4 *HST* cycles by Lauroesch:

HST GO 12191 - PI Lauroesch "Prospecting for Rare Elements in the Interstellar Medium", data acquisition completed, data analysis completed, publication in preparation.

HST SNAP 12192 - PI Lauroesch "A SNAPSHOT Survey of Interstellar Absorption Lines", data acquisition complete, publication detailing temporal variations toward HD 210809 in preparation. A second publication detailing limits on temporal variations toward repeated stars in planning.

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APPENDIX B

OBSERVATIONAL METADATA

The tables included in this chapter have correspondence with Tables 5.1 - 5.11 in Chapter 5. These tables contain the observational metadata from the Elodie archive spectra. Annotations and table order match those in Chapter 4.

TABLE B.1
Observational Metadata for Non-OB Measurable Targets – A

Target $^{\alpha}$	File $^{\beta}$	Date $^{\gamma\delta}$	ExpTime $^{\gamma}$ 10^3s	S/N $^{\gamma\epsilon}$
¹ HD 332329	20040704 0017	2004-07-05 23:54:13	1.800	48.2
² HD 192640	19990604 0032	1999-06-05 01:50:37	1.384	323.9
³ HD 185732	19990707 0016	1999-07-07 23:14:31	3.001	101.3
⁴ HD 184471	19940924 0009	1994-09-24 19:12:07	0.702	23.0
⁵ HD 191747	19990813 0024	1999-08-13 22:27:47	1.410	322.6
⁶ BD+314105	19940918 0013	1994-09-18 20:28:02	0.901	19.3
⁷ HD 184875	19960728 0014	1996-07-28 22:15:11	0.458	180.0
⁸ HD 184006	20050826 0013	2005-08-26 21:05:55	0.500	298.6
⁹ HD 182989	19960625 0040	1996-06-26 00:50:34	1.685	116.0
¹⁰ HD 190397	20060624 0017	2006-06-25 00:11:05	1.800	57.5
¹¹ HD 197345	20040823 0040	2004-08-23 22:52:39	0.060	336.8
¹² HD 172167A	19960502 0040	1996-05-03 03:03:07	0.062	483.8
¹³ HD 195692A	20010807 0022	2001-08-07 22:23:57	0.600	146.2
¹⁴ HD 188854A	20000721 0024	2000-07-21 22:46:41	1.801	145.2
¹⁵ HD 200723	19990813 0031	1999-08-14 00:54:29	2.812	297.6
¹⁶ HD 198343	20001005 0017	2000-10-05 20:54:15	3.001	162.1
¹⁷ HD 173977	20020920 0007	2002-09-20 18:49:18	7.201	193.2
¹⁸ HD 186155	19990810 0023	1999-08-10 21:44:50	1.306	298.3
¹⁹ BD+293448	19940924 0008	1994-09-24 18:56:43	0.701	16.6
²⁰ HD 194093	19960823 0020	1996-08-23 22:12:43	0.120	513.5
²¹ HD 198226A	19990817 0020	1999-08-18 01:11:59	1.570	92.5
²² HD 190537A	20000720 0021	2000-07-21 00:14:39	0.901	147.0
²³ HD 335198	20000709 0007	2000-07-09 22:27:17	4.501	46.9
²⁴ HD 341233	20000805 0006	2000-08-05 20:15:56	3.601	51.1
²⁵ BD+344217	20000908 0010	2000-09-08 21:32:39	4.501	56.5
²⁶ HD 190508	20050805 0015	2005-08-05 23:34:58	1.200	32.7
²⁷ BD+433754	20010727 0006	2001-07-27 21:20:26	4.501	36.6
²⁸ HD 200019	20000804 0013	2000-08-04 22:01:55	1.201	113.8
²⁹ HD 199939	20020622 0045	2002-06-23 00:53:25	0.481	78.6
³⁰ HD 199178	19981124 0019	1998-11-24 17:49:33	1.501	121.7

$^{\alpha}$ Numbers correspond to annotations in Figure 5.2 and Tables 5.1 - 5.2.

$^{\beta}$ Elodie file names given by “elodie:yyyymmdd/nnnn”.

$^{\gamma}$ Metadata taken directly from FITS headers.

$^{\delta}$ At the beginning of the exposure. Format is yyyy-mm-dd hh : mm : ss

$^{\epsilon}$ As reported by the archive.

TABLE B.2
Observational Metadata for Non-OB Measurable Targets – B

Target ^α	File ^β	Date ^{γδ}	ExpTime ^γ 10 ³ s	S/N ^{γϵ}
³¹ HD 335070	20010825 0012	2001-08-25 21:57:14	4.501	54.4
³² HD 193891	20000706 0007	2000-07-06 20:53:03	1.201	105.9
³³ HD 170527	20031103 0009	2003-11-03 18:07:57	2.700	166.4
³⁴ HD 198149	19950911 0017	1995-09-11 21:23:23	0.300	405.2
³⁵ BD+483149	20010731 0030	2001-08-01 00:27:20	1.501	84.0
³⁶ HD 332698	20031004 0011	2003-10-04 20:05:47	5.563	78.1
³⁷ HD 187372	20000809 0018	2000-08-09 22:12:40	0.601	182.9
³⁸ HD 186619	20030703 0023	2003-07-03 23:23:47	0.300	76.5
³⁹ HD 186532	20030703 0021	2003-07-03 23:08:41	0.360	61.1
⁴⁰ HD 177808	20030703 0013	2003-07-03 21:39:20	0.360	79.5
⁴¹ HD 172381	20010802 0035	2001-08-03 00:01:44	0.421	52.2
⁴² HD 190964	20030703 0029	2003-07-04 00:17:46	0.300	54.3
⁴³ HD 197939	20030703 0031	2003-07-04 00:45:06	0.300	47.2

^α Numbers correspond to annotations in Figure 5.2 and Tables 5.1 - 5.2.

^β Elodie file names given by “elodie:yyyymmdd/nnnn”.

^γ Metadata taken directly from FITS headers.

^δ At the beginning of the exposure. Format is yyyy–mm–dd hh : mm : ss

^ϵ As reported by the archive.

TABLE B.3
Observational Metadata for Non-OB No Absorption Targets – A

Target ^α	File ^β	Date ^{γδ}	ExpTime ^γ 10 ³ s	S/N ^{γϵ}
¹ HD 335238	19940715 0017	1994-07-15 22:32:22	0.000	104.7
² HD 196542A	19940918 0016	1994-09-18 21:14:04	0.901	27.9
³ HD 173648	19990809 0015	1999-08-09 20:56:26	0.785	325.9
⁴ HD 191158	20000722 0034	2000-07-23 01:18:42	0.600	75.6
⁵ HD 174567	20060531 0016	2006-06-01 00:04:02	3.602	92.7
⁶ HD 180583	19950908 0008	1995-09-08 19:35:27	1.801	257.6
⁷ HD 174912A	19961005 0007	1996-10-05 18:55:30	1.503	104.3
⁸ HD 181096	19970827 0019	1997-08-27 21:09:31	0.801	88.8
⁹ BD+443670	20000706 0009	2000-07-06 21:57:26	1.801	71.5
¹⁰ HD 183361A	20000717 0015	2000-07-17 23:39:45	1.201	137.3
¹¹ HD 171635	20030326 0017	2003-03-27 04:01:33	0.301	158.7
¹² HD 176051	20030709 0009	2003-07-09 21:42:21	0.900	226.8
¹³ HD 171485A	20030715 0011	2003-07-15 22:39:16	1.200	95.7
¹⁴ HD 195992	20030801 0024	2003-08-02 00:30:11	0.900	82.5
¹⁵ HD 195295	20031101 0011	2003-11-01 18:40:40	0.240	217.3
¹⁶ HD 185395	20031105 0021	2003-11-05 17:57:14	0.720	330.7
¹⁷ HD 180712	20040731 0013	2004-07-31 22:19:37	1.200	70.7
¹⁸ HD 195872	20040731 0017	2004-07-31 23:27:00	1.200	75.6
¹⁹ HD 173700	20041124 0011	2004-11-24 17:09:51	1.200	98.1
²⁰ HD 192804	20050630 0014	2005-07-01 01:08:19	1.200	31.9
²¹ HD 172323A	20050711 0012	2005-07-12 00:56:40	1.520	55.7
²² HD 198084	20050714 0013	2005-07-15 00:31:14	0.500	152.2
²³ HD 184960	20050716 0033	2005-07-17 01:40:47	0.900	170.5
²⁴ HD 184448	20051023 0008	2005-10-23 19:18:51	1.801	67.5
²⁵ HD 186408	19960414 0022	1996-04-15 03:18:37	0.900	160.5
²⁶ HD 196850	19960830 0010	1996-08-30 23:00:04	0.901	122.2
²⁷ HD 175306A	19961004 0008	1996-10-04 18:37:01	0.123	120.3
²⁸ HD 199191	19970615 0019	1997-06-16 01:00:09	0.601	111.9
²⁹ HD 185501A	19970721 0029	1997-07-22 00:46:27	0.901	120.3
³⁰ HD 191022	19970722 0032	1997-07-23 01:32:51	0.901	101.3

^α Numbers correspond to annotations in Figure 5.3 and Tables 5.3 - 5.4.

^β Elodie file names given by “elodie:yyyymmdd/nnnn”.

^γ Metadata taken directly from FITS headers.

^δ At the beginning of the exposure. Format is yyyy–mm–dd hh : mm : ss

^ϵ As reported by the archive.

TABLE B.4
Observational Metadata for Non-OB No Absorption Targets – B

Target ^α	File ^β	Date ^{γδ}	ExpTime ^γ 10 ³ s	S/N ^{γϵ}
³¹ HD 191649	19970817 0032	1997-08-17 23:44:52	0.901	120.3
³² HD 185414	19970818 0015	1997-08-18 22:21:58	0.901	178.1
³³ HD 187237	19970909 0021	1997-09-09 20:53:22	0.721	126.5
³⁴ HD 186427	19980808 0010	1998-08-08 21:03:54	0.601	156.2
³⁵ HD 188326A	19980808 0018	1998-08-08 23:24:01	0.901	119.3
³⁶ HD 187462	19980810 0015	1998-08-10 22:30:06	0.701	119.9
³⁷ HD 197310	19980810 0020	1998-08-11 00:12:43	0.900	111.5
³⁸ HD 195988	19980901 0018	1998-09-01 22:25:17	0.901	109.3
³⁹ HD 187123A	19990916 0036	1999-09-16 20:51:41	0.901	88.4
⁴⁰ HD 198483	19990926 0017	1999-09-26 20:21:45	0.300	46.4
⁴¹ HD 198809	20000706 0015	2000-07-07 00:31:12	0.301	218.1
⁴² HD 184499	20030710 0032	2003-07-11 23:56:30	0.900	136.1
⁴³ HD 188650	20031101 0010	2003-11-01 18:12:46	1.500	261.1
⁴⁴ HD 176377	20040706 0007	2004-07-06 23:25:16	1.805	186.2
⁴⁵ HD 197666	20040726 0029	2004-07-27 00:41:51	1.200	48.3
⁴⁶ HD 187792	20040729 0012	2004-07-29 22:33:34	1.200	79.7
⁴⁷ HD 187748	20040731 0014	2004-07-31 22:42:52	0.600	101.6
⁴⁸ HD 187876	20040731 0015	2004-07-31 22:58:00	1.200	87.5
⁴⁹ HD 190771	20040901 0012	2004-09-01 20:01:19	1.800	273.5
⁵⁰ HD 189749	20040927 0010	2004-09-27 20:53:50	1.200	63.7
⁵¹ HD 170357	20041122 0017	2004-11-22 17:10:24	1.201	47.7
⁵² HD 182758	20041123 0012	2004-11-23 17:14:01	1.200	57.5
⁵³ HD 181047	20050528 0021	2005-05-29 02:09:04	1.100	54.4
⁵⁴ HD 196361	20050803 0013	2005-08-03 23:25:06	1.200	28.2
⁵⁵ HD 172393	20050805 0010	2005-08-05 21:45:23	1.200	48.8
⁵⁶ HD 175441	20050913 0007	2005-09-13 19:23:26	1.500	64.6
⁵⁷ HD 185269	20060608 0028	2006-06-09 01:25:25	2.400	139.3
⁵⁸ HD 176670	19960902 0009	1996-09-02 20:35:23	0.601	227.7
⁵⁹ HD 188947	19970828 0014	1997-08-28 22:52:29	0.091	126.5
⁶⁰ HD 199870	20021028 0017	2002-10-28 21:03:10	0.902	220.8

^α Numbers correspond to annotations in Figure 5.3 and Tables 5.3 - 5.4.

^β Elodie file names given by “elodie:yyyymmdd/nnnn”.

^γ Metadata taken directly from FITS headers.

^δ At the beginning of the exposure. Format is yyyy–mm–dd hh : mm : ss

^ϵ As reported by the archive.

TABLE B.5
Observational Metadata for Non-OB Inconclusive Targets – A

Target	File β	Date $\gamma\delta$	ExpTime γ 10^3s	S/N $\gamma\epsilon$
BD+293427	19940918 0009	1994-09-18 19:16:24	0.801	18.7
HD 340577	19940918 0015	1994-09-18 20:52:00	0.901	27.6
HD 200405	19940918 0023	1994-09-18 23:35:40	0.703	26.6
HD 191742	19940919 0009	1994-09-19 20:01:26	1.203	26.0
HD 192678	19940924 0012	1994-09-24 20:01:23	0.603	51.3
HD 195725	19990809 0021	1999-08-09 22:40:21	1.004	316.4
HD 177196	19990813 0019	1999-08-13 20:54:11	1.600	303.4
HD 183534	20060531 0018	2006-06-01 01:10:57	4.501	154.1
BD+353616A	19940918 0010	1994-09-18 19:36:40	0.602	17.4
HD 341037	19940924 0015	1994-09-24 20:55:23	0.801	27.7
HD 197572	19960822 0011	1996-08-22 21:00:20	0.000	324.6
HD 198726	19960823 0027	1996-08-24 00:01:34	2.001	257.3
BD+423935	19970614 0020	1997-06-15 00:59:00	0.601	19.7
HD 238932A	19970617 0017	1997-06-17 23:51:12	0.301	18.9
BD+423607	19970822 0008	1997-08-22 20:57:07	3.602	59.7
HD 194951	19990706 0018	1999-07-07 02:29:49	0.900	81.7
HD 331319	19990709 0016	1999-07-10 01:06:21	5.401	98.1
HD 195069	20030625 0017	2003-06-26 00:15:07	7.202	560.0
HD 193370	20030725 0014	2003-07-26 00:30:27	0.660	241.1
HD 200805	20030729 0010	2003-07-30 00:13:00	4.501	152.7
HD 178593	20040801 0011	2004-08-01 22:23:03	1.506	103.7
HD 188307	20040802 0016	2004-08-03 23:55:22	1.200	28.6
HD 187253	20050722 0034	2005-07-23 00:41:41	1.200	31.8
HD 185239	20050913 0008	2005-09-13 19:55:05	1.500	75.3
HD 175225	19960503 0033	1996-05-04 02:09:59	0.601	216.8
HD 173701	19961023 0025	1996-10-23 18:00:10	0.901	133.0
HD 177153	19970820 0011	1997-08-20 20:55:14	0.901	132.8
HD 185351	19970823 0006	1997-08-23 20:29:39	0.630	267.0
BD+413931	19970823 0012	1997-08-23 22:30:41	3.601	68.2
HD 175306	19970827 0016	1997-08-27 20:02:16	0.601	24.4

β Elodie file names given by “elodie:yyyymmdd/nnnn”.

γ Metadata taken directly from FITS headers.

δ At the beginning of the exposure. Format is yyyy–mm–dd hh : mm : ss

ϵ As reported by the archive.

TABLE B.6
Observational Metadata for Non-OB Inconclusive Targets – B

Target	File $^{\beta}$	Date $^{\gamma\delta}$	ExpTime $^{\gamma}$ $10^3 s$	S/N $^{\gamma\epsilon}$
HD 182488	19980901 0009	1998-09-01 20:02:18	0.901	163.6
HD 175900	19990814 0014	1999-08-14 22:37:57	0.904	91.8
HD 193795	19990926 0015	1999-09-26 20:05:14	0.300	33.7
HD 200391	20000707 0007	2000-07-07 21:35:17	1.201	95.2
HD 181655	20000731 0015	2000-07-31 23:06:50	0.751	183.9
BD+364301	20000804 0016	2000-08-04 23:21:21	3.601	74.8
HD 179484A	20000813 0020	2000-08-13 22:27:28	1.801	73.8
HD 190360A	20000824 0023	2000-08-24 23:03:32	0.721	206.8
HD 178911A	20010402 0032	2001-04-03 02:59:15	1.201	107.3
HD 199598	20010721 0021	2001-07-22 00:46:46	0.901	151.9
HD 173605	20010728 0005	2001-07-28 20:09:56	1.501	127.5
HD 190228	20010811 0015	2001-08-11 22:12:07	0.901	125.9
HD 188326	20010812 0017	2001-08-12 22:25:24	1.501	112.7
HD 187123	20010814 0018	2001-08-14 22:52:25	1.001	96.4
HD 182736	20011010 0022	2001-10-10 21:42:19	0.901	116.6
HD 171242	20011011 0012	2001-10-11 19:32:37	0.901	75.5
HD 185657	20021028 0015	2002-10-28 20:24:06	1.343	200.9
HD 171007	20030521 0022	2003-05-22 00:49:22	1.801	42.3
HD 193216A	20030715 0013	2003-07-15 23:21:17	0.900	50.1
HD 178911B	20030717 0020	2003-07-18 00:47:04	0.900	117.0
HD 200102	20030725 0019	2003-07-26 02:02:02	3.001	258.1
HD 190403	20030727 0011	2003-07-27 23:26:14	3.601	156.8
HD 174104	20030729 0007	2003-07-29 20:08:57	5.001	122.4
HD 191010	20030729 0009	2003-07-29 22:53:58	4.201	149.7
HD 180161	20040710 0010	2004-07-11 00:43:52	2.401	129.8
HD 180683	20040726 0024	2004-07-26 22:57:15	1.200	50.4
HD 197037	20040726 0027	2004-07-27 23:53:04	1.200	75.0
HD 180502	20040728 0012	2004-07-28 22:20:08	1.200	80.1
HD 197488	20040728 0016	2004-07-29 23:58:53	1.200	79.0
HD 175425	20040926 0012	2004-09-26 19:17:56	1.200	57.1

$^{\beta}$ Elodie file names given by “elodie:yyyymmdd/nnnn”.

$^{\gamma}$ Metadata taken directly from FITS headers.

$^{\delta}$ At the beginning of the exposure. Format is *yyyy-mm-dd hh:mm:ss*

$^{\epsilon}$ As reported by the archive.

TABLE B.7
Observational Metadata for Non-OB Inconclusive Targets – C

Target	File β		Date $\gamma\delta$	ExpTime γ $10^3 s$	S/N $\gamma\epsilon$
HD 193215	20041001	0010	2004-10-01 19:11:51	1.200	57.1
HD 172557	20041002	0009	2004-10-02 18:44:12	1.200	60.3
HD 184601	20041002	0011	2004-10-02 19:30:53	1.200	69.1
HD 199100	20041002	0013	2004-10-02 20:16:51	1.200	91.8
HD 195987	20041009	0008	2004-10-09 17:53:28	1.802	126.3
HD 187548	20050529	0016	2005-05-30 00:28:37	1.500	43.9
HD 177780	20050530	0015	2005-05-31 01:51:44	1.500	22.8
HD 190605	20050616	0029	2005-06-17 02:09:52	1.200	82.6
HD 178911	20050711	0011	2005-07-12 00:25:49	1.017	110.0
HD 178450	20050714	0009	2005-07-14 22:56:23	2.108	88.6
HD 173024	20050723	0015	2005-07-23 21:41:57	1.200	35.2
HD 173289	20050725	0022	2005-07-26 00:05:31	1.200	38.3
HD 197140	20050805	0016	2005-08-06 00:02:23	1.200	44.3
HD 197207	20050912	0014	2005-09-12 21:36:10	1.500	58.4
HD 189087	19961023	0026	1996-10-23 18:19:44	0.801	103.7
HD 234677	19970521	0013	1997-05-22 00:54:31	3.601	134.7
HD 197989	19970823	0010	1997-08-23 21:16:55	0.021	204.7
HD 183255	19970924	0011	1997-09-24 19:45:41	5.401	215.5
HD 191026	19971108	0009	1997-11-08 18:31:03	1.200	226.7
HD 338867	19980318	0029	1998-03-19 03:24:27	0.602	43.7
HD 199956	20000708	0006	2000-07-08 22:08:06	2.401	140.0
HD 334514	20000709	0006	2000-07-09 21:06:31	4.501	36.1
HD 199546	20010730	0018	2001-07-30 20:39:07	1.201	91.2
HD 189806	20010731	0024	2001-07-31 20:28:22	1.201	76.8
HD 181209	20010731	0025	2001-07-31 20:55:43	1.202	68.2
HD 188056	20010809	0028	2001-08-09 22:28:08	0.603	95.3
BD+333930	20010825	0011	2001-08-25 21:11:28	2.401	124.5
BD+334140	20010826	0009	2001-08-26 21:53:42	3.601	58.8
HD 192787	20021022	0008	2002-10-22 18:07:01	1.641	261.8
HD 196134	20021027	0014	2002-10-27 20:49:15	2.401	209.3

β Elodie file names given by “elodie:yyyymmdd/nnnn”.

γ Metadata taken directly from FITS headers.

δ At the beginning of the exposure. Format is yyyy–mm–dd hh : mm : ss

ϵ As reported by the archive.

TABLE B.8
Observational Metadata for Non-OB Inconclusive Targets – D

Target	File β		Date $\gamma\delta$	ExpTime γ	S/N $\gamma\epsilon$
				$10^3 s$	
HD 176408	20021028	0013	2002-10-28 19:57:56	0.900	274.0
HD 198550	20030711	0031	2003-07-12 00:47:33	0.900	59.4
HD 192910	20030725	0013	2003-07-26 00:14:37	0.360	152.3
HD 193469	20030726	0017	2003-07-27 02:15:11	2.101	188.3
HD 198794	20030727	0012	2003-07-28 00:32:39	3.600	114.6
HD 200560	20031102	0010	2003-11-02 19:16:11	3.602	139.7
HD 190470	20040712	0012	2004-07-13 01:33:42	3.300	70.5
BD+413306	20040819	0017	2004-08-19 21:05:36	3.600	85.2
BD+522815	20040902	0009	2004-09-02 20:41:52	5.401	95.9
HD 332518	20040907	0008	2004-09-07 20:43:30	6.301	84.6
HD 331093	20040926	0014	2004-09-26 20:05:21	1.200	36.8
HD 191806	20040928	0008	2004-09-28 20:18:13	1.200	66.8
HD 171607	20041002	0008	2004-10-02 18:21:04	1.200	70.1
HD 179094	20050625	0022	2005-06-26 02:16:58	0.600	118.5
HD 198425	20050703	0019	2005-07-04 01:25:28	1.200	51.0
HD 188753	20051025	0006	2005-10-25 18:54:47	1.801	111.1
BD+400883	19940928	0015	1994-09-28 19:51:46	3.601	35.1
HD 173739	19970524	0023	1997-05-23 22:20:39	2.701	109.2
GJ 0747	19970812	0018	1997-08-12 21:10:39	2.402	29.2
GJ 0809	19980723	0020	1998-07-24 00:35:53	1.201	75.4
HD 186686	19980805	0018	1998-08-05 23:18:11	1.801	204.8
GJ 0725	19990702	0012	1999-07-02 23:44:29	1.201	63.0
BD+394208	19990821	0014	1999-08-21 21:24:26	5.952	164.2
BD+364025	19990823	0014	1999-08-23 20:26:11	7.201	152.9
HD 182190	20000809	0017	2000-08-09 21:57:55	0.601	190.7
HD 199871	20000809	0021	2000-08-09 22:55:12	0.900	131.3
HD 186776	20000810	0014	2000-08-10 22:09:23	0.601	141.0
HD 175865	20010809	0025	2001-08-09 21:36:41	0.601	255.7
HD 175588	20010810	0013	2001-08-10 21:21:48	0.181	93.1
HD 184786	20010812	0014	2001-08-12 21:46:43	0.361	121.1

β Elodie file names given by “elodie:yyyymmdd/nnnn”.

γ Metadata taken directly from FITS headers.

δ At the beginning of the exposure. Format is yyyy–mm–dd hh : mm : ss

ϵ As reported by the archive.

TABLE B.9
Observational Metadata for Non-OB Inconclusive Targets – E

Target	File ^{β}		Date ^{$\gamma\delta$}	ExpTime ^{γ} $10^3 s$	S/N ^{$\gamma\epsilon$}
GJ 0815	20010902	0018	2001-09-02 21:36:39	1.201	29.7
GJ 0766	20011030	0010	2001-10-30 19:09:25	3.601	12.7
HD 189063	20020618	0027	2002-06-19 01:53:06	0.482	79.8
HD 178003	20030703	0014	2003-07-03 21:49:54	0.360	49.3
HD 180450	20030703	0017	2003-07-03 22:23:43	0.360	45.2
HD 179869	20030703	0018	2003-07-03 22:34:21	0.401	52.3
HD 187849	20030703	0024	2003-07-03 23:32:47	0.300	98.5
HD 190544	20030703	0026	2003-07-03 23:52:15	0.300	88.8
HD 199305	20040818	0013	2004-08-18 22:22:13	3.601	81.3
HD 173740	20040822	0011	2004-08-22 21:34:21	7.201	104.9
HD 331161	19940925	0014	1994-09-25 20:14:54	3.601	17.6
HD 190163	20000809	0020	2000-08-09 22:34:45	0.900	67.4
HD 182917	20030703	0019	2003-07-03 22:44:36	0.500	50.6
GJ 0802	20050922	0012	2005-09-22 21:11:31	3.601	4.9

^{β} Elodie file names given by “elodie:yyyymmdd/nnnn”.

^{γ} Metadata taken directly from FITS headers.

^{δ} At the beginning of the exposure. Format is *yyyy-mm-dd hh:mm:ss*

^{ϵ} As reported by the archive.

TABLE B.10
Observational Metadata for OB Targets – A

Target	File β	Date $\gamma\delta$	ExpTime γ 10^3s	S/N $\gamma\epsilon$
HD 188209	19970917 0012	1997-09-17 21:36:34	1.803	417.5
HD 198820	20041110 0019	2004-11-10 19:10:20	3.601	161.1
HD 194335	19970921 0027	1997-09-21 23:04:10	1.201	243.6
HD 200120	20030808 0014	2003-08-08 22:09:33	1.200	376.4
HD 182255	20031106 0018	2003-11-06 17:37:00	3.601	512.2
HD 338529	19970822 0009	1997-08-22 22:04:28	3.601	83.9
HD 183056	20000519 0019	2000-05-20 01:15:20	1.801	268.1
HD 174638	20010906 0025	2001-09-06 21:22:35	0.241	249.7
HD 176437	19960425 0031	1996-04-26 02:27:27	0.301	64.5
HD 180163	19981128 0015	1998-11-28 18:33:38	0.090	114.3
HD 192685	20030819 0020	2003-08-19 22:17:13	0.901	371.6
HD 198183	20040823 0041	2004-08-23 23:05:39	0.600	85.9
BD+404124	19970707 0008	1997-07-07 22:02:19	5.401	62.9
HD 194279	19970919 0021	1997-09-19 22:39:34	3.601	296.8
HD 172324	20001008 0011	2000-10-08 19:51:41	6.001	152.9
BD+413731	19970708 0011	1997-07-08 22:27:27	3.601	93.6
HD 193322A	20050817 0007	2005-08-17 19:33:11	1.200	54.6
HD 193322	20040829 0016	2004-08-29 23:18:09	1.200	189.4
HD 195592	19970918 0029	1997-09-18 20:52:24	3.601	322.8
HD 190864	20010812 0018	2001-08-12 22:56:35	2.402	144.2
HD 191423	20040829 0013	2004-08-29 19:39:37	5.401	150.5
HD 189957	20040827 0014	2004-08-27 19:38:55	2.701	137.0
HD 192639	20010811 0018	2001-08-11 22:49:26	0.721	129.6
HD 191978	20040829 0014	2004-08-29 21:14:58	5.401	125.7
HD 190429	20040827 0015	2004-08-27 20:39:05	1.500	174.4
HD 199579	19970921 0016	1997-09-21 20:49:31	1.508	248.1
HD 193514	20040828 0008	2004-08-29 00:04:36	2.401	129.4
HD 190429A	20051106 0008	2005-11-06 18:38:01	3.601	154.9
HD 186980	20010811 0014	2001-08-11 21:43:19	1.501	136.0
HD 193443	20040828 0007	2004-08-28 23:08:18	1.800	157.5

β Elodie file names given by “elodie:yyyymmdd/nnnn”.

γ Metadata taken directly from FITS headers.

δ At the beginning of the exposure. Format is yyyy–mm–dd hh : mm : ss

ϵ As reported by the archive.

TABLE B.11
Observational Metadata for OB Targets – B

Target	File ^{β}		Date ^{$\gamma\delta$}		ExpTime ^{γ} $10^3 s$	S/N ^{$\gamma\epsilon$}
HD 191612	20040828	0003	2004-08-28 19:16:22		3.601	152.4
HD 192281	20040828	0005	2004-08-28 21:33:21		2.701	153.0
HD 191201	20040827	0017	2004-08-27 21:43:10		1.600	142.4
HD 193237	19980614	0031	1998-06-15 01:02:40		1.800	250.5
HD 198478	20040824	0038	2004-08-24 21:44:20		0.900	158.0
HD 228712	19970917	0011	1997-09-17 19:28:57		7.201	226.3
HD 194839	19970919	0008	1997-09-19 18:52:58		5.401	279.9

^{β} Elodie file names given by “elodie:yyyymmdd/nnnn”.

^{γ} Metadata taken directly from FITS headers.

^{δ} At the beginning of the exposure. Format is *yyyy-mm-dd hh:mm:ss*

^{ϵ} As reported by the archive.

APPENDIX C

SOURCE CODE

The following appendix contains most of the relevant source code for the **SLiPy** library. Each *module* is included in its own section for which the name reflects the file structure to that module. Some modules are not included for practical reasons. The code is self documenting using Python's *docstring* functionality (accounting for some of its length). The software can be downloaded from its *GitHub* repository at <http://github.com/glentner/slipy> or from its website at <http://glentner.github.io/slipy>. For interactive, human readable documentation visit the website. The code can be downloaded via several formats including *zip* and *tar.gz* or can be *cloned* directly to your desktop.

The **LICENSE** and **README** file have been omitted. This content can be accessed online. Also, the **AtomicData** module has been omitted intentionally. It would occupy up to a hundred or more pages of raw data in the form of a Python list and serves no benefit to be included here. Neither are any of the files from the **SLiPy.Data.Archives** included.

C.1 .. __init__

```
1  # Copyright (c) Geoffrey Lentner 2015. All Rights Reserved.
2  # See LICENSE (GPLv3)
3  # SLiPy/___init__.py
4  """
5  SLiPy - A Spectroscopy and astrophysics Library for Python 3
6
7  This Python package is an expanding code base for doing computational
8  astronomy, particularly spectroscopy. It contains both a *Spectrum* class
9  for handling spectra as objects (with +, -, \*, /, etc... operations defined)
10 and a growing suite of analysis tools.
11 """
12
13 # base exception class for whole project, module exception classes will
14 # be derived from here.
15 class SlipyError(Exception):
16     pass
17
18 # exposed modules
19 from .SLiPy import Fits, Simbad, Correlate, Telluric, Velocity, \
20     Observatory, Montage, Plot, Spectrum, Measure, Profile
21
22 # elevate 'Spectrum' to the package level
23 from .SLiPy.Spectrum import Spectrum
```

C.2 .. Algorithms . Functions

```
1  # Copyright (c) Geoffrey Lentner 2015. All Right Reserved.
2  # See LICENSE (GPLv3)
3  # slipy/Algorithms/Functions.py
4  """
5  Analytical functions used in SLiPy.
6  """
7
8  import numpy as np
9  from scipy.special import wofz as w # Faddeeva function
10
11  # No FunctionsError implimented yet
12
13  def Gaussian(x, *params):
14      """
15      The Gaussian function. The function template has '*params' to work with
16      scipy...curve_fit; the user *must* specify 'A, mu, sigma = params'.
17      """
18      A, mu, sigma = params
19      return A * np.exp( -0.5 * (x - mu)**2 / sigma**2 )
20
21  def NormalizedGaussian(x, *params):
22      """
23      The normalized Gaussian function.
24      """
25      mu, sigma = params
26      return np.exp( -0.5 * (x - mu)**2 / sigma**2 ) / (sigma *
27      np.sqrt(2 * np.pi))
28
29  def InvertedGaussian(x, *params):
30      """
31      An inverted Gaussian function (i.e., 1 - Guassian()). The function
32      template has '*params' to work with scipy...curve_fit; the user *must*
33      specify 'A, mu, sigma = params'.
34      """
35      return 1 - Gaussian(x, *params)
36
37  def Lorentzian(x, *params):
38      """
39      The Lorentzian function. Typically used to describe an absorption line profile.
40      """
41      x0, gamma = params
42      return 1 / ((2 * (x - x0) / gamma)**2 + 1)
43
44  def NormalizedLorentzian(x, *params):
45      """
46      The Lorentzian function, normalized.
47      """
48      x0, gamma = params
49      return 2 * Lorentzian(x, *params) / (np.pi * gamma)
50
51  def NormalizedVoigt(x, *params):
52      """
53      The Voigt function. The result of the convolution of a Lorentzian with one or more
54      Gaussians. Often used to describe an intrinsically Lorentzian absorption profile blurred
55      by Gaussian broadening from thermal motions and turbulence and another Gaussian instrument
56      profile. The result is also the real part of the Faddeeva function (the complex probability
57      function), implemented by Scipy as wofz in scipy.special
58
59      This returns a normalized profile. The name 'NormalizedVoigt' is to keep the convention
60      for the rest of this module. The amplitude controlling Voigt profile 'Voigt' evaluates
61      this function first for 'x - x0 = 0' to empirically 'un-normalize' it before scaling by the
62      requested amplitude
63
64      Reference:
65      Olivero, J.J; R.L. Longbothum. 'Empirical fits to the Voigt line width:
66      A brief review'. Journal of Quantitative Spectroscopy and Radiative Transfer. Vol 17.
67      Issue 2. pages 223-236. Feb 1977
68
69      Parameters: 'x0, sigma, gamma = params'
70
71      x0 -> center of the profile
72      sigma -> the Gaussian width
73      gamma -> the Lorentzian width
74      """
75      x0, sigma, gamma = params
76      return w( ((x-x0) + 1j*gamma) / (sigma * np.sqrt(np.pi)) ).real / (
77      sigma * np.sqrt(2 * np.pi) )
78
79  def Voigt(x, *params):
80      """
81      The Voigt line profile. See ..Algorithms.Function.NormalizedVoigt for more information.
82      This function returns an amplitude controlled Voigt profile.
83
84      Parameters: 'A, x0, sigma, gamma = params'
85
86      A -> amplitude of the profile
87      x0 -> center of the profile
88      sigma -> the Gaussian width
89      gamma -> the Lorentzian width
```



```

90         """
91         return params[0] * NormalizedVoigt(x, *params[1:]) / NormalizedVoigt(0, 0, *params[2:])
92
93
94     def InvertedLorentzian(x, *params):
95         """
96         An inverted Lorentzian (i.e, A - Lorentzian()).
97         """
98         A, x0, gamma = params
99
100         return A - Lorentzian(x, x0, gamma)

```

C.3 .. Algorithms . KernelFit

```
1  # Copyright (c) Geoffrey Lentner 2015. All Right Reserved.
2  # See LICENSE (GPLv3)
3  # slipy/Algorithms/KernelFit.py
4  """
5  Non-parametric Kernel Regression.
6  """
7
8  import numpy as np
9
10 from .. import SlipyError
11 from ..Framework.Options import Options, OptionsError
12
13 from .Functions import Gaussian
14
15 class KernelFitError(SlipyError):
16     """
17     Exception specific to the KernelFit module
18     """
19
20 class KernelFit1D():
21     """
22     One dimensional kernel regression.
23     """
24     def __init__(self, x, y, kernel = Gaussian, **kwargs):
25         """
26         Keep the input 'x' and 'y' arrays. Define parameters.
27         The default kernel function is the Gaussian. Alternatives should
28         have the same signature as slipy.Algorithms.Functions.Gaussian
29         """
30         if not hasattr(x, '__iter__') or not hasattr(y, '__iter__'):
31             raise KernelFitError('Both 'x' and 'y' are expected to '
32                                   'be array-like!')
33
34         if len(np.shape(x)) != 1 or len(np.shape(y)) != 1:
35             raise KernelFitError('Both 'x' and 'y' are expected to '
36                                   'be one-dimensional objects!')
37
38         if len(x) != len(y):
39             raise KernelFitError('Both 'x' and 'y' should be of the '
40                                   'same length!')
41
42         if not hasattr(x, 'copy') or not hasattr(y, 'copy'):
43             raise KernelFitError('Both 'x' and 'y' should have a '
44                                   'copy() method implimented!')
45
46         if type(x) is not type(y):
47             raise KernelFitError('Both 'x' and 'y' are expected to '
48                                   'be of the same type!')
49
50         if hasattr(x, 'unit') and not hasattr(y, 'unit'):
51             raise KernelFitError('The 'x' array given has units but the 'y' '
52                                   'array doesn't!, maybe give 'y' u.dimensionless_unscaled?')
53
54         if hasattr(y, 'unit') and not hasattr(x, 'unit'):
55             raise KernelFitError('The 'y' array given has units but the 'x' '
56                                   'array doesn't!, maybe give 'x' u.dimensionless_unscaled?')
57
58         # the default 'bandwidth' is 1/10 the domain of 'x', this
59         # is likely to be a bad choice!
60         bandwidth = 0.1 * (x.max() - x.min())
61
62         try:
63
64             options = Options( kwargs, {
65
66                 'bandwidth' : bandwidth # for the kernel function
67             })
68
69             self.kernel      = kernel
70             self.bandwidth = options('bandwidth') # not necessarily with units
71
72         except OptionsError as err:
73             print(' --> OptionsError:', err)
74             raise KernelFitError('Unrecognized option for KernelFit1D(!)')
75
76         self.x = x.copy()
77         self.y = y.copy()
78
79     def mean(self, x):
80         """
81         Solve for smooth profile through the data on the new 'x' array.
82         This is essentially a weighted mean.
83         """
84
85         if not hasattr(x, '__iter__'):
86             raise KernelFitError('x' is expected to be array-like!')
87
88         if not hasattr(x, 'copy'):
89             raise KernelFitError('x' is expected to have a copy() method!')
```

```

90
91     if hasattr(x, 'unit') and not hasattr(self.x, 'unit'):
92         raise KernelFitError('The provided array has units but the '
93                               'original domain does not!')
94
95     if hasattr(self.x, 'unit') and not hasattr(x, 'unit'):
96         raise KernelFitError('The provided array does not have units '
97                               'but the original domain did!')
98
99     # copy 'x' such that the return type is the same as the input type
100    y = x.copy()
101
102    # fix units though
103    if hasattr(x, 'unit'):
104        y = y.value * self.y.unit
105
106    for a, point in enumerate(x):
107
108        weights = Gaussian(point, 1, self.x, self.bandwidth)
109
110        # weights should be dimensionless
111        if hasattr(x, 'unit'):
112            weights = weights.decompose()
113
114        args = np.where(np.isfinite(self.y))
115        y[a] = np.sum(weights[args] * self.y[args]) / np.sum(weights[args])
116
117    return y

```

C.4 .. Data . Atomic

```
1  # Copyright (c) Geoffrey Lentner 2015. All Rights Reserved.
2  # See LICENSE (GPLv3)
3  # slipy/Data/Atomic.py
4
5  """
6  Access methods for the atomic data published by Donald C. Morton (2003).
7  See .Archives.AtomicData.MortonTable
8  """
9
10 import numpy as np
11 from astropy import units as u
12
13 from .. import SlipyError
14 from ..Framework.Options import Options, OptionsError
15 from .Archives import AtomicData
16
17 class AtomicError(SlipyError):
18     """
19     Exception specific for the IonManager class.
20     """
21     pass
22
23 class IonManager:
24     """
25     Managing class for the atomic data (Morton 2003). See SLiPy.Data.Archives.AtomicData.
26     """
27     def __init__(self):
28         """
29         Imports the atomic data and creates the dictionary.
30         """
31         self.data = AtomicData.MortonTable
32
33         # march through the table and apply units, compute oscillator strengths
34         for a, entry in enumerate(self.data):
35
36             AirWave = None if not entry[0] else entry[0] * u.Angstrom
37             VacWave = None if not entry[1] else entry[1] * u.Angstrom # shouldn't happen?
38             Ion = entry[2]
39
40             # conversion from 'cm-1' (Mohr & Taylor 2000)
41             ELow = entry[3] * 1.23984186 * u.eV
42
43             # solve for oscillator strengths
44             Logwf = entry[4]
45             os = None if not Logwf else 10**(Logwf) / VacWave.value
46
47             self.data[a] = [AirWave, VacWave, Ion, ELow, Logwf, os]
48
49         # build dictionary by ion name
50         self.ions = { ion : [] for ion in set([entry[2] for entry in self.data]) }
51         for entry in self.data:
52             self.ions[ entry[2] ].append( entry[:2] + entry[3:] )
53
54     def __call__(self, key, **kwargs):
55         """
56         Retrieve data from the Archives.AtomicData table. If the 'key' is a string
57         type it is expected to be the name of an ion (e.g., 'C III'). If the 'key' is
58         a number it is expected to be a wavelength value (if not with units Angstroms are
59         implied). The default is Vacuum wavelength, but Air can be specified with the
60         keyword argument 'wavelength='Air''.
61
62         If the key was the name of an ion, all the lines for that ion are returned. If the
63         key was a wavelength, the closest line in the table to that wavelength is returned.
64         You can request a wavelength range by giving the 'key' as a tuple of two wavelengths
65         specifying the range.
66
67         The results default to the f-value (a.k.a. the oscillator strength) but can be
68         changed with the keyword argument 'entry'. Options include, 'Air', 'Vacuum', 'Ion',
69         'ELow', 'LOGWF', and 'fvalue'.
70
71         The if either a single pair or a list of pairs: the first element of each pair is
72         always a wavelength value (in Air if wavelength='Air' or in Vacuum otherwise), the
73         second being the entries requested. The wavelength type is always that used for
74         the look-up. That is, Vacuum by default, but if 'wavelength='Air'' is given, the
75         returns will be in Air wavelengths. Be aware that 'None' might be returned if
76         there is not Air wavelength for the line. Further, all results will be returned
77         as 'None' where no data is available.
78         """
79         try:
80             options = Options( kwargs, {
81
82                 'wavelength' : 'vacuum', # alternative is 'air'
83                 'lookup' : 'fvalue' # others: 'air', 'vacuum', 'ion', 'elow', 'logwf'
84             })
85
86             wavelength = options('wavelength')
87             lookup = options('lookup')
```

```

90     except OptionsError as err:
91         print('--> OptionsError:', err)
92         raise AtomicError('Failed keyword assignment from __call__ to IonManager!')
93
94     if isinstance(key, tuple):
95
96         if len(key) != 2:
97             raise AtomicError('tuples expected to be length 2 on __call__ to '
98                               'IonManager!')
99
100         table = self.Between(*key)
101
102     else:
103
104         table = self.__getitem__(key)
105
106     # map entries to index value
107     lookup_options = { 'air': 0, 'vacuum': 1, 'ion': 2, 'elow': 3, 'logwf': 4, 'fvalue' : 5 }
108
109     if lookup not in lookup_options:
110         raise AtomicError('{}' is not an available search option!'.format(lookup))
111
112     if wavelength not in ['air', 'vacuum']:
113         raise AtomicError('Only 'air' and 'vacuum' wavelengths are understood!')
114
115     if isinstance(key, str):
116
117         # alter the index dictionary for column changes
118         lookup_options = { 'air': 0, 'vacuum': 1, 'elow': 2, 'logwf': 3, 'fvalue' : 4 }
119
120         if lookup == 'ion':
121             # 'Ion' column won't be present in the returned 'table' !!!
122             raise AtomicError('You provided the name of an ion but requested the names '
123                               'of the ions as the return value!')
124
125     if not isinstance(key, tuple) and not isinstance(key, str):
126         # assume this was a single wavelength value, 'table' is a single line
127         return tuple([ table[ lookup_options[wavelength] ], table[ lookup_options[lookup] ] ])
128
129     return [# return pairs of wavelength and 'lookup' for each 'line' found
130            tuple([ line[ lookup_options[wavelength] ], line[ lookup_options[lookup] ] ])
131            for line in table
132            ]
133
134 def __getitem__(self, index):
135     """
136     Access methods.
137
138     If the 'index' is a string value giving the name of a particular ion, this method
139     returns the entries in the data for that ion.
140
141     If the 'index' is a numerical value, this method returns the table entry closest
142     in wavelength (vacuum).
143
144     If the 'index' is a slice object (e.g., '5850:5950') it returns the segment of the
145     table data on that range. A 'step' is not acceptable (e.g., '::0.5').
146     """
147     if isinstance(index, slice):
148
149         start, stop, step = index.start, index.stop, index.step
150
151         if step: raise AtomicError('You cannot slice the table with a 'step' size!')
152
153         if not start:
154             # the first vacuum wavelength in the table
155             start = self.data[0][1]
156
157         if not stop:
158             # the last vacuum wavelength in the table
159             stop = self.data[-1][1]
160
161         return self.Between(start, stop)
162
163     elif isinstance(index, str):
164
165         if index not in self.ions:
166             raise AtomicError('{}' is not a recognized or available ion in the '
167                               'data!'.format(index))
168
169         return self.ions[index]
170
171     else:
172
173         if hasattr(index, 'unit'):
174             index = index.to(u.Angstrom).value
175
176         proximity = (np.array([entry[1].value for entry in self.data]) - index)**2
177
178         return self.data[ proximity.argmax() ]
179
180 def Below(self, wavelength):
181     """
182     Return all table entries below the given wavelength. If units are not given,

```

```

183     Angstroms are implied.
184     """
185     if not hasattr(wavelength, 'unit'):
186         wavelength *= u.Angstrom
187
188     if wavelength > self.data[-1][1] or wavelength < self.data[0][1]:
189         raise AtomicError('Cannot access wavelengths outside the data available!')
190
191     return [ entry for entry in self.data if entry[1] < wavelength ]
192
193 def Above(self, wavelength):
194     """
195     Return all table entries below the given wavelength. If units are not given,
196     Angstroms are implied.
197     """
198     if not hasattr(wavelength, 'unit'):
199         wavelength *= u.Angstrom
200
201     if wavelength > self.data[-1][1] or wavelength < self.data[0][1]:
202         raise AtomicError('Cannot access wavelengths outside the data available!')
203
204     return [ entry for entry in self.data if entry[1] > wavelength ]
205
206 def Between(self, wavelengthA, wavelengthB):
207     """
208     Return all table entries between the given wavelengths. If units are not given,
209     Angstroms are implied.
210     """
211     if not hasattr(wavelengthA, 'unit'):
212         wavelengthA *= u.Angstrom
213
214     if not hasattr(wavelengthB, 'unit'):
215         wavelengthB *= u.Angstrom
216
217     if wavelengthA > self.data[-1][1] or wavelengthA < self.data[0][1]:
218         raise AtomicError('Cannot access wavelengths outside the data available!')
219
220     if wavelengthB > self.data[-1][1] or wavelengthB < self.data[0][1]:
221         raise AtomicError('Cannot access wavelengths outside the data available!')
222
223     if wavelengthA > wavelengthB:
224         # that doesn't make sense, switch the order
225         wavelengthA, wavelengthB = wavelengthB, wavelengthA
226
227     return [ entry for entry in self.Below(wavelengthB) if entry[1] > wavelengthA ]
228
229
230 # create a static instance of the IonManager class.
231 IonSearch = IonManager()
232
233 class Ion():
234     """
235     An object for declaring atomic ions.
236
237     An 'Ion' should have a name, wavelength (air or vacuum), oscillator strength,
238     and a transition probability (Einstein coefficient).
239
240     Much of this data is available from the ..Data.Archives.AtomicData module searchable
241     with the ..Data.Atomic.IonManager class. In the future, we hope to implement an
242     internal database of transition probabilities for each ion in the AtomicData module
243     from the Morton 2003 publication. Currently, the user must provide this data.
244
245     The NIST Atomic Spectra Database Lines Data is a good source for atomic data values:
246     http://physics.nist.gov/PhysRefData/ASD/lines_form.html
247     """
248     def __init__(self, name=None, wavelength=None, fvalue=None, A=None, **kwargs):
249         """
250         Create a new 'Ion'. If no arguments are given the state remains uninitialized.
251         The 'name' (e.g., 'Ca III') is used to connect with the data in the
252         ..Data.Archives.AtomicData module via the IonManager class. The 'wavelength' need
253         not necessarily be the exact value of the line; the line closest to that given
254         for the 'name'd ion is used. This is by default the wavelength in vacuum, but can
255         be the wavelength in air if the keyword argument 'medium='air'' is given.
256         The created member attribute 'wavelength' and 'fvalue' are automatically assigned
257         based on this procedure, but can be explicitly assigned if the 'fvalue' is
258         provided directly. The transition probability (Einstein coefficient) 'A' simply
259         attached as 'A'. If not units are given for 'A', 's-1' is assigned.
260         """
261         try:
262             options = Options( kwargs, {
263
264                 'medium' : 'vacuum' # alternative is 'air'
265             })
266
267             self.medium = options('medium')
268
269             if self.medium not in ['vacuum', 'air']:
270                 raise AtomicError('From Ion.__init__(), the only allowed values for 'medium' '
271                                     'are 'vacuum' and 'air'!')
272
273         except OptionsError as err:
274

```

```

275         print(' --> OptionsError:', err)
276         raise AtomicError('From Ion.__init__(), that was not an exceptable keyword assignment '
277                             'for an 'Ion!')
278
279     if not name or not wavelength or fvalue:
280         # simply assign whatever is provided.
281         self.name = name
282         self.wavelength = wavelength
283         self.fvalue = fvalue
284         self.A = A
285
286     else:
287
288         if not hasattr(wavelength, 'unit'):
289             wavelength *= u.Angstrom
290
291         # lookup the ion using IonManager (already created as IonSearch)
292         found_ions = IonSearch(name, wavelength=self.wavelength)
293         wavelengths = np.array([(wavelength - entry[0]).value for entry in found_ions])**2
294         closest_ion = wavelengths.argmin()
295
296         # assign the closest wavelength to that available
297         self.wavelength = found_ions[ closest_ion ][0].to(wavelength.unit)
298         self.fvalue = found_ions[ closest_ion ][1] * u.dimensionless_unscaled
299
300         self.name = name
301
302         if A and not hasattr(A, 'unit'):
303             A /= u.s
304
305         self.A = A
306
307     def __str__(self):
308         """
309         Show the available information for this Ion.
310         """
311         return ('Ion:      {}\n'
312                 'Wavelength: {}\n'
313                 'fvalue:     {}\n'
314                 'A:         {}'.format(self.name, self.wavelength, self.fvalue, self.A))
315
316     def __repr__(self):
317         """
318         The same as the 'str' representation.
319         """
320         return str(self)

```

C.5 .. Data . Elodie

```

1  # Copyright (c) Geoffrey Lentner 2015. All Rights Reserved.
2  # See LICENSE (GPLv3)
3  # AstroPython/Data/Elodie.py
4  """
5  Methods for data retrieval from the Elodie Archive.
6  """
7
8  import os, shutil, numpy as np
9  from urllib.request import urlopen
10
11  from .. import SlipyError
12  from ..Framework.Options import Options, OptionsError
13  from ..Framework.Display import Monitor, DisplayError
14
15
16  class ElodieError(SlipyError):
17      """
18      Exception specific to Elodie module.
19      """
20      pass
21
22  class Archive:
23      """
24      Import and parse ascii catalog of Elodie archive files. The complete
25      archive is stored in the member 'data'. It's organized in a dictionary
26      by unique target names. Each target has a list of pairs consisting of the
27      name of the file and the signal to noise for that spectrum. The reduced
28      archive, accessed with 'files', contains identified 'HD', 'HR', 'BD', 'GC',
29      and 'GJ' objects, choosing the file pertaining to the spectra with the
30      highest signal-to-noise ratio available.
31      """
32      def __init__(self, **kwargs):
33          try:
34
35              # default input file
36              default_infile = os.path.join( os.path.dirname(__file__),
37              'Archives/Elodie.csv')
38
39              # parameter defaults
40              options = Options( kwargs,
41              {
42                  'infile' : default_infile, # path to input file
43                  'catalogs': ['HD','BD','HR','GC','GJ'] # catalogues to keep
44              })
45
46              # parameter assignments
47              infile = options('infile')
48              catalogs = options('catalogs')
49
50          except OptionsError as err:
51              print(' --> OptionsError:', err)
52              raise ElodieError('Failed keyword assignment from Archive.__init__')
53
54          # import data from archive
55          with open(infile, 'r') as archive:
56              data = [ line.split(',') for line in archive.readlines() ]
57
58          # strip elements of white space
59          data = [ [x.strip() for x in line] for line in data ]
60
61          # build empty dictionary of unique names with empty lists
62          targets = { name:[] for name in set([ line[0] for line in data ]) }
63
64          # compile list of spectra files organized by identifier w/ S/N
65          for line in data:
66              targets[line[0]].append( line[2:] )
67
68          # reject files from spectra not in catalogues
69          targets = { k:v for k, v in targets.items() if k[:2] in catalogs }
70
71          files = {}
72          for target, options in targets.items():
73              # choose best S/N
74              idx = np.array( np.array(options)[:,-1], dtype=np.int_ ).argmax()
75              files[target] = options[idx][0]
76
77          # members
78          self.data = targets
79          self.files = files
80          self.names = [
81              '-'.join('-'.join(x.split(':')).split('/')) + '.fits'
82              for x in files.values()
83          ]
84
85  def Script(filename, pipeline=''):
86      """
87      Construct url script for Elodie archive given 'filename' and optionally
88      'pipeline' instructions (e.g., '&z=wrs|fca[1,nor]').
89      """

```



```

90     return ''.join(['http://atlas.obs-hp.fr/elodie/E.cgi?&c=i&o=',
91                     filename, pipeline, '&a=mime:application/x-fits'])
92
93 def Download( *files, **kwargs ):
94     """
95     Download 'files' from Elodie archive via url scripts. The spectra can be
96     further reduced via Elodie's pipeline with the following options.
97
98     kwargs = {
99         'verbose' : True           , # display messages, progress
100         'resample' : (min, max, res), # resample spectra (no default)
101         'normalize' : True         , # continuum normalization
102         'outpath' : './'          , # directory for downloaded files
103         'names' : []              , # alternative output names for 'files'
104     }
105     """
106     try:
107         # function parameter defaults
108         options = Options( kwargs,
109                             {
110                                 'verbose' : True           , # display messages, progress
111                                 'resample' : (-1,-1,-1), # handled by Elodie
112                                 'normalize' : True         , # continuum normalization
113                                 'outpath' : './'          , # directory for downloaded files
114                                 'names' : []              , # alternative output names for 'files'
115                             })
116
117         # function parameter assignments
118         verbose = options('verbose')
119         resample = options('resample')
120         normalize = options('normalize')
121         outpath = options('outpath')
122         names = options('names')
123
124         # check for 'resampled' assignment
125         if 'resample' not in kwargs:
126             resample = None
127         elif len(resample) != 3:
128             raise ElodieError('Download() expects 'resample' to be of length '
129                               'three.')
130
131         # set default names
132         if not names:
133             names = [ '-'.join(fname.split(':')) for fname in files ]
134             names = [ '-'.join(fname.split('/')) for fname in names ]
135             names = [ fname + '.fits' for fname in names ]
136
137         elif len(names) != len(files):
138             raise ElodieError('Download() expects 'names' option to be of '
139                               'length equal to that of the number of 'files' arguments.')
140
141     except OptionsError as err:
142         print(' --> OptionsError:', err)
143         raise ElodieError('Failed keyword assignment from Download().')
144
145     if not resample and not normalize:
146         pipeline = ''
147     else:
148         pipeline = '&z=wrs'
149
150     if normalize:
151         pipeline += '|fca[1,nor]'
152
153     if resample:
154         resample = [ str(x) for x in resample ]
155         pipeline += '|wrs[1,' + ','.join(resample) + ']'
156
157     if verbose:
158         display = Monitor(ETC=True)
159         nfiles = len(files)
160         print('\n Downloading {} files from Elodie ...'.format(nfiles))
161
162     for a, spectra in enumerate(files):
163         # show progress
164         if verbose: display.progress(a + 1, nfiles)
165
166         # download file
167         with urlopen( Script(spectra, pipeline) ) as response, open(
168             os.path.join(outpath, names[a]), 'wb') as outfile:
169             shutil.copyfileobj(response, outfile)
170
171     if verbose:
172         display.complete()
173         display.elapsed()
174
175

```

C.6 .. Framework . Argument

```
1  # Copyright (c) Geoffrey Lentner 2015. All Rights Reserved.
2  # See LICENSE (GPLv3)
3  # slipy/Framework/Arguments.py
4  """
5  Module contains 'Argument' class for handling conversions and type
6  checking for function/class keyword argument options.
7  """
8
9  from .. import SlipyError
10
11  class ArgumentError(SlipyError):
12      """
13      Exception specific to Argument module.
14      """
15      pass
16
17  class Argument:
18      """
19      'Argument' object has type and value management.
20      """
21      def __init__(self, value, name = 'unspecified', **kwargs ):
22          """
23          Build Argument 'value', 'type', and set 'options'.
24          """
25          options = {
26              'lock' : False # disallow all type conversions
27          }
28          for arg in kwargs:
29              if arg not in options:
30                  raise ArgumentError('{} is not an option for Argument.'
31                                     .format(arg))
32              if type(kwargs[arg]) is not type(options[arg]):
33                  raise ArgumentError('Option {} expects {}, given {}'.format(
34                                     arg, type(options[arg]), type(kwargs[arg])) )
35              # accept reassignment
36              options[arg] = kwargs[arg]
37
38          self.lock = options['lock']
39          self.T = type(value)
40          self.value = value
41          self.name = str(name)
42          if type(name) is not str:
43              raise ArgumentError('Argument expects type str for name.')
44
45      def __call__(self, value):
46
47          if self.lock and type(value) is not self.T:
48              raise ArgumentError('Argument {} is locked as {}, '
49                                 'but new value has {}'.format(
50                                 self.name, self.T, type(value)) )
51
52          if self.T is bool:
53              # special rules for 'bool' conversions
54
55              if type(value) is str:
56                  if value != "True" and value != "False":
57                      raise ArgumentError('Invalid conversion from {} '
58                                         'for Argument {}'.format(self.T, self.name))
59                  self.value = True if value == 'True' else False
60
61              elif type(value) is int:
62                  if value != 0 and value != 1:
63                      raise ArgumentError('Invalid conversion from {} '
64                                         'for Argument {}'.format(self.T, self.name) )
65                  else:
66                      self.value = True if value else False
67
68              elif type(value) is not bool:
69                  raise Error('Invalid conversion from {} '
70                             'for Argument {}'.format(self.T, self.name))
71
72          else: self.value = value
73
74      else:
75
76          try:
77              self.value = self.T(value)
78
79          except ValueError as error:
80              raise ArgumentError('Cannot convert {} to {} for {}'.format(
81                                 'Argument.'.format(self.T, type(value), self.name))
```

C.7 .. Framework . Command

```
1  # Copyright (c) Geoffrey Lentner 2015. All Rights Reserved.
2  # See LICENSE (GPLv3).
3  # slipy/Framework/Interface.py
4  """
5  Command line interface tools.
6  """
7
8  from .. import SlipyError
9  from .Options import Options, OptionsError
10
11 class CommandError(SlipyError):
12     """
13     Exception specific to Command module.
14     """
15     pass
16
17 def Parse( clargs, **kwargs ):
18     """
19     Parse command line arguments, 'clargs' (i.e., sys.argv).
20     """
21     if type(clargs) is not list:
22         raise CommandError('Parse function expects a list for 'clargs'.')
23     try:
24         options = Options( kwargs,
25                             {
26                                 'exe' : True # search first argument for '@func' pattern
27                             })
28
29         if options('exe'):
30             function = clargs[0].split('@')
31             if len(function) != 2 or function[0]:
32                 raise CommandError('Incorrect formatting in function call.')
33             function = function[1]
34             del(clargs[0])
35
36         # args should not have an assignment
37         args = [ x for x in clargs if '=' not in x ]
38
39         # remaining clargs should be kwargs
40         kwargs = {
41             key : value for key, value in [
42                 arg.split('=') for arg in set(clargs) - set(args)
43             ]
44         }
45
46         if options('exe'):
47             return function, args, kwargs
48
49         else:
50             return args, kwargs
51
52     except OptionsError as err:
53         print('\n --> OptionsError:', err)
54         raise CommandError('from Parse')
55
56     except ValueError as key:
57         raise CommandError('Incorrect formatting of keyword arguments.')
```

C.8 .. Framework . Display

```
1  # Copyright (c) Geoffrey Lentner 2015. All Rights Reserved.
2  # See LICENSE (GPLv3)
3  # slipy/Framework/Display.py
4  """
5  Display - Python module for displaying content to the terminal.
6  """
7
8  import os, sys, math
9  from time import time
10 from datetime import datetime, timedelta
11
12 from .. import SlipyError
13 from .Options import Options, OptionsError
14
15 class DisplayError(SlipyError):
16     """
17     Exception specific to the Display module.
18     """
19     pass
20
21 class Monitor:
22     """
23     Class for displaying a progress bar during iterative tasks.
24     """
25     def __init__(self, **kwargs):
26         try:
27             # available keyword options
28             self.options = Options( kwargs,
29                 {
30                     'width' : 45 , # number of characters wide
31                     'numbers' : True , # display numerical percent
32                     'template' : '[=>]', # template for progress bars
33                     'freq' : 0.25 , # refresh rate
34                     'ETC' : False , # display estimated time of completion
35                     'inline' : True , # vanish after completion
36                 })
37
38             # give assignments
39             self.width = self.options('width')
40             self.numbers = self.options('numbers')
41             self.freq = self.options('freq')
42             self.ETC = self.options('ETC')
43             self.inline = self.options('inline')
44             self.left, self.char, self.tip, self.right = self.options('template')
45
46             # start clocks
47             self.start = time()
48             self.last = time()
49
50         except OptionsError as err:
51             print( '\n --> OptionsError:', err.msg )
52             raise DisplayError('Failed to initialize Monitor.')
53
54         except ValueError as err:
55             raise DisplayError(
56                 "'template' option requires exactly 4 characters.")
57
58     def __EstimatedCompletionTime(self):
59         """
60         Estimated time of completion, based on percent complete and
61         current total elapsed time.
62         """
63         if self.percent > 0:
64             elapsed = time() - self.start
65             remaining = elapsed * (1 / self.percent - 1)
66             etc = datetime.today() + timedelta(seconds=remaining)
67             return etc.strftime(' ETC: %Y-%m-%d @ %H:%M ')
68
69     def __build(self):
70         """
71         Build the progress bar
72         """
73         bars = self.char * math.floor( self.percent * self.width )
74         empty = ' ' * (self.width - len(bars) - 1)
75         display = self.left + bars + self.tip + empty + self.right
76
77         if self.numbers:
78             display += '{:>8.2f} % '.format( self.percent * 100 )
79
80         if self.ETC:
81             display += self.__EstimatedCompletionTime()
82
83         sys.stdout.write('\r \033[K \r {}'.format(display))
84         sys.stdout.flush()
85
86     def progress(self, i, imax):
87         """
88         Request a progress bar.
89         """
```

```

90     if time() - self.last > self.freq:
91         # refresh rate surpassed,
92         # update time of last call and percent complete
93         self.last = time()
94         self.percent = float(i) / float(imax)
95         # display progress bar
96         self._build()
97
98     def complete(self):
99         """
100         Call to finalize the progress bar.
101         """
102         if self.inline:
103             sys.stdout.write('\r\033[K\r')
104             sys.stdout.flush()
105         else:
106             self.percent = 1
107             self.numbers = False
108             self.ETC = False
109             self._build()
110             sys.stdout.write(' complete\n')
111             sys.stdout.flush()
112
113     def elapsed(self):
114         """
115         Display total time elapsed since instantiation.
116         """
117         total = time() - self.start
118         abrv = [ 'd', 'h', 'm', 's' ]
119         unit = { 'd': 86400, 'h': 3600, 'm': 60 }
120         count = { 'd': 0, 'h': 0, 'm': 0, 's': 0 }
121
122         for item in abrv:
123             if item in unit:
124                 while total > unit[item]:
125                     total -= unit[item]
126                     count[item] += 1
127             else: count[item] = math.floor(total)
128
129         total = [
130             '{} {}'.format( v, u )
131             for u, v in zip( abrv, [ count[v] for v in abrv ] )
132             if count[u]
133         ]
134         total = ' Time Elapsed: ' + ' '.join(total)
135         total = ' ' + '-' * (len(total)+5) + '\n ' + total
136
137         sys.stdout.write(total)
138         sys.stdout.flush()
139

```

C.9 .. Framework . Measurement

```
1  # Copyright (c) Geoffrey Lentner 2015. All Rights Reserved.
2  # See LICENSE (GPLv3)
3  # slipy/Framework/Measurement.py
4  """
5  The 'Measurement' is a container for a 'value' and 'error'.
6
7  Astropy already has a very useful object, 'Quantity' that is expanded into
8  a 'Constant' class. Something with a value, a name, abbreviation, uncertainty,
9  and a reference. A 'Measurement' is nothing more than a 'Constant' by
10 a different name. It functions just like a Quantity/Constant, only we don't
11 want to be calling it a "constant" and we want to be able to have many of them.
12 """
13
14 from astropy.units import Quantity
15
16 class Measurement(Quantity):
17     """
18     A container for a 'result' and an 'error'. This object is meant to be functionally
19     equivalent to the astropy.constant.Constant, without the instance checking (we can
20     have many 'Measurement's). There are 'notes' instead of 'references'.
21     """
22     def __new__(cls, value, error=None, name=None, notes=None):
23
24         instance = super().__new__(cls, value)
25
26         instance.error = error
27         instance.name = name
28         instance.notes = notes
29
30         return instance
31
32     # These operations are 'broken' because they would otherwise yield a 'Measurement'.
33     # The right handed operations are not affected, these are all that is needed I think.
34     def __truediv__(self, other):
35         return Quantity(super().__truediv__(other))
36
37     def __mul__(self, other):
38         return Quantity(super().__mul__(other))
39
40     def __add__(self, other):
41         return Quantity(super().__add__(other))
42
43     def __sub__(self, other):
44         return Quantity(super().__sub__(other))
45     # -----
46
47     def __repr__(self):
48         return '<' + ' '.join([label + str(attr) for attr, label in zip(['Measurement',
49             self.value * self.unit, self.error, self.name, self.notes],
50             ['', '', '| error = ', '| name = ', '| notes = ']) if attr]) + '>'
51
52     def __str__(self):
53         attr = [ self.name, self.value*self.unit, self.error, self.notes ]
54         name = [ ' Name = {}', ' Value = {}', ' Error = {}', ' Notes = {}' ]
55         show = [ a for a in attr if a ]
56         return '\n'.join([n for a, n in zip(attr, name) if a]).format(*show)
```

C.10 .. Framework . Options

```
1  # Copyright (c) Geoffrey Lentner 2015. All Rights Reserved.
2  # See LICENSE (GPLv3)
3  # slipy/Framework/Options.py
4  """
5  Class object for handling kwargs in classes and functions.
6  """
7
8  from .. import SlipyError
9  from .Argument import Argument as Arg, ArgumentError
10
11  class OptionsError(SlipyError):
12      """
13      Exception specific to Options module.
14      """
15      pass
16
17  class Options:
18      """
19      Class object for handling kwargs in classes and functions.
20      """
21      def __init__(self, kwargs, options ):
22          """
23          Check types and build options dictionary
24          """
25          try:
26              # initial assignment
27              self.options = {
28                  name : Arg(value, name)
29                  for name, value in options.items()
30              }
31              # attempted reassignment
32              for key, value in kwargs.items():
33                  self.options[key](value)
34
35          except AttributeError as err:
36              raise OptionsError(
37                  'Options object expects dictionary types.')
38
39          except KeyError as key:
40              raise OptionsError(
41                  '{} was not a recognized option.'.format(key))
42
43          except ArgumentError as err:
44              print('\n --> ArgumentError:', err.msg )
45              raise OptionsError('Failed assignment.')
46
47      def __call__(self, option):
48          """
49          Retrieve value of 'option'.
50          """
51          try:
52              return self.options[option].value
53          except KeyError as key:
54              raise OptionsError('{} was not recognized.'.format(key))
55
56      def items(self):
57          """
58          Access options.items() values.
59          """
60          return { k:v.value for k,v in self.options.items() }.items()
```

C.11 .. SLiPy . Correlate

```
1  # Copyright (c) Geoffrey Lentner 2015. All Rights Reserved.
2  # See LICENSE (GPLv3)
3  # slipy/SLiPy/Correlate.py
4  """
5  Correlate - Module of correlation functions for astronomical data.
6  """
7  import numpy as np
8
9  from .. import SlipyError
10 from .Spectrum import Spectrum, SpectrumError
11 from ..Framework.Options import Options, OptionsError
12
13 class CorrelateError(SlipyError):
14     """
15     Exception specific to Correlate module.
16     """
17     pass
18
19 def RMS( array ):
20     """
21     RMS( array ):
22
23     Return the root mean square of an 'array'.
24     """
25     if type(array) is not np.ndarray or len(np.shape(array)) != 1:
26         raise CorrelateError('RMS() expects 1D numpy.ndarray's.')
27
28     return np.sqrt( ( array**2 ).sum() ) / len(array)
29
30 def Xcorr( spectrumA, spectrumB, **kwargs ):
31     """
32     Xcorr( spectrumA, spectrumB, **kwargs ):
33
34     Cross correlate two spectra of equal pixel length. The function returns
35     an integer value representing the best shift within a 'lag' based on
36     the computed RMS of each configuration.
37     """
38     try:
39         # define 'options' for Xcorr()
40         options = Options( kwargs,
41                             {
42                                 'lag' : 25 # pixels to shift for correlation
43                             } )
44
45         # check argument types, values
46         if ( type(spectrumA) is not Spectrum or
47             type(spectrumB) is not Spectrum ):
48             raise CorrelateError('Xcorr() expects 'Spectrum' arguments.')
49
50         elif len(spectrumA.data) != len(spectrumB.data):
51             raise CorrelateError('Xcorr() expects 'Spectrum' arguments to '
52             'be of equal length.')
53
54         # assign 'lag' and the pixel length of the spectra
55         lag = options('lag')
56         npix = len(spectrumA.data)
57
58         # resample 'B' to wavelength space of 'A'
59         spectrumB.resample(spectrumA)
60
61         # arrays to correlate
62         A = spectrumA.data.value
63         B = spectrumB.data.value
64
65         # shift spectra 'left' over each other
66         left = np.array([ RMS(diff) for diff in [ A[-shift:] -
67             B[:shift] for shift in range(-lag,0) ] ])
68
69         # shift spectra 'right' over each other
70         right = np.array([ RMS(diff) for diff in [ A[:-shift] -
71             B[shift:] for shift in range(1,lag+1) ] ])
72
73         # include 'zero' shift in rms vector.
74         rms = np.hstack((left, RMS(A - B), right))
75
76         # return the shift corresponding to the minimum RMS
77         return rms.argmin() - lag
78
79     except OptionsError as err:
80         print(' --> OptionsError:', err)
81         raise CorrelateError('Inappropriate keyword arguments passed '
82             ' to Xcorr().')
```


C.12 .. SLiPy . Fits

```
1  #!/usr/bin/env python
2  # Copyright (c) Geoffrey Lentner 2015. All Rights Reserved.
3  # See LICENSE (GPLv3)
4  # slipy/SLiPy/Fits.py
5  """
6  Fits - FITS file handling module.
7  """
8  import os, sys, fnmatch
9  from astropy.io import fits as pyfits
10 from numbers import Number
11
12 from .. import SlipyError
13 from ..Framework.Command import Parse, CommandError
14 from ..Framework.Options import Options, OptionsError
15 from ..Framework.Display import Monitor, DisplayError
16 from .Spectrum import Spectrum, SpectrumError
17 from .Simbad import Position, Distance, Sptype, IDList, SimbadError
18
19 class FitsError(SlipyError):
20     """
21     Exception for Fits module.
22     """
23     pass
24
25 def Find(toplevel = './', pattern = '*.fits'):
26     """
27     Search for file paths below 'toplevel' fitting 'pattern'.
28     """
29     if not os.path.isdir(toplevel):
30         raise FitsError('{} does not name a directory.'.format(toplevel))
31
32     return [ os.path.join(toplevel, filename)
33             for filename in fnmatch.filter(os.listdir(toplevel), pattern) ]
34
35 def RFind(toplevel = './', pattern = '*.fits'):
36     """
37     Recursively search for paths below 'toplevel' fitting 'pattern'.
38     """
39     if not os.path.isdir(toplevel):
40         raise FitsError('{} does not name a directory.'.format(toplevel))
41
42     return [ os.path.join(dirpath, filename)
43             for dirpath, dirnames, filenames in os.walk(toplevel)
44             for filename in fnmatch.filter(filenames, pattern) ]
45
46 def GetData( *files, **kwargs ):
47     """
48     Import data from FITS 'files'.
49     """
50     kwargs = {
51         'verbose' : True, # display messages, progress
52         'toplevel' : '', # request import from directory 'toplevel'
53         'pattern' : '*.fits', # pattern matching with 'toplevel'
54         'recursive' : False, # search recursively below 'toplevel'
55         'wavecal' : True, # fit wavelength vector to data
56         'crpix1' : 'crpix1', # reference pixel header keyword
57         'crval1' : 'crval1', # value at reference pixel
58         'cdelt1' : 'cdelt1', # resolution (delta lambda)
59     }
60
61     try:
62         # convert 'files' to list
63         files = list(files)
64
65         # available key word arguments
66         options = Options( kwargs,
67                             {
68                                 'verbose' : True, # display messages, progress
69                                 'toplevel' : '', # request import from 'toplevel' dir
70                                 'pattern' : '*.fits', # pattern matching with 'toplevel'
71                                 'recursive' : False, # search recursively below 'toplevel'
72                                 'wavecal' : True, # fit wavelength vector to data
73                                 'crpix1' : 'crpix1', # reference pixel header keyword
74                                 'crval1' : 'crval1', # value at reference pixel
75                                 'cdelt1' : 'cdelt1', # resolution (delta lambda)
76                             })
77
78         # assignment options
79         verbose = options('verbose')
80         toplevel = options('toplevel')
81         pattern = options('pattern')
82         recursive = options('recursive')
83         wavecal = options('wavecal')
84         crpix1 = options('crpix1')
85         crval1 = options('crval1')
86         cdelt1 = options('cdelt1')
87
88         if toplevel:
89             # search for files matching 'pattern'
```

```

90     find = RFind if recursive else Find
91     files += find( toplevel, pattern )
92
93     if verbose:
94         # import iteratively, displaying progress
95         display = Monitor()
96         nfiles = len(files)
97         data = []
98         print(' Importing data from {} Fits files ...'.format(nfiles) )
99         for a, filename in enumerate(files):
100             display.progress(a, nfiles)
101             data.append( Spectrum(filename, wavecal=wavecal,
102                                crpix1=crpix1, crval1=crval1, cdelt1=cdelt1) )
103
104     display.complete()
105     return data
106
107     # import spectra 'silently'
108     return [ Spectrum(filename, wavecal=wavecal, crpix1=crpix1,
109                        crval1=crval1, cdelt1=cdelt1) for filename in files ]
110
111 except OptionsError as err:
112     print(' --> OptionsError:', err)
113     raise FitsError('Data retrieval failure.')
114
115 except SpectrumError as err:
116     print(' --> SpectrumError:', err)
117     raise FitsError('Failed to construct spectrum.')
118
119 def Header( filename, keyword = None, **kwargs ):
120     """
121     Retrieve 'keyword' from FITS header in 'filename'. If not provided a
122     keyword, the entire header object is returned.
123     """
124     try:
125         options = Options( kwargs,
126                             {
127                                 'is_main' : False # reserved for calls from Main()
128                             })
129
130         is_main = options('is_main')
131
132         with pyfits.open(filename) as hdulist:
133             header = hdulist[0].header
134             if keyword: header = header[keyword]
135
136         if is_main:
137             print( header )
138             return
139
140         else:
141             return header
142
143     except OptionsError as err:
144         print(' --> OptionsError:', err)
145         raise FitsError('Failed keyword assignment in Header().')
146
147     except KeyError as key:
148         raise FitsError('Header element '{}' was not accessible '
149                        'from {}'.format(keyword, filename))
150
151 def Search( *files, **kwargs ):
152     """
153     Extract object names from Fits 'files' and use Simbad.py
154     to resolve the 'attribute' (a required keyword argument)
155     from the SIMBAD astronomical database.
156
157     kwargs = {
158         verbose : True      , # display messages, progress
159         toplevel : ''       , # search under 'toplevel' directory
160         pattern : '*.fits'  , # for files under 'toplevel'
161         recursive : False   , # search recursively under 'toplevel'
162         attribute : ''      , # attribute to search for (no default)
163     }
164     """
165     try:
166         # convert 'files' to list
167         files = list(files)
168
169         # available keyword arguments
170         options = Options( kwargs,
171                             {
172                                 'verbose' : True      , # display messages, progress
173                                 'toplevel' : ''       , # search under 'toplevel' directory
174                                 'pattern' : '*.fits'  , # for files under 'toplevel'
175                                 'recursive' : False   , # search recursively under 'toplevel'
176                                 'attribute' : ''      , # attribute to search for (no default)
177                                 'is_main' : False     , # reserved for calls from Main()
178                             })
179
180     # assign parameters

```

```

183     verbose = options('verbose')
184     toplevel = options('toplevel')
185     pattern = options('pattern')
186     recursive = options('recursive')
187     attribute = options('attribute')
188     is_main = options('is_main')
189
190     # Available search functions from Simbad.py
191     SimbadSearch = {
192         'Position': Position, # ra, dec (degrees)
193         'Distance': Distance, # in parsecs
194         'Sptype' : Sptype , # spectral type
195         'IDList' : IDList    # alternate IDs
196     }
197
198     if not attribute:
199         raise FitsError('An 'attribute' must be specified for Search().')
200
201     if attribute not in SimbadSearch:
202         raise FitsError('{}' is not an available search criteria.'
203             .format(attribute))
204
205     if toplevel:
206         # search for files in 'toplevel' directory
207         find = RFind if recursive else Find
208         files += find(toplevel, pattern)
209
210     nfiles = len(files)
211     display = Monitor()
212
213     if verbose:
214         # read object names iteratively
215         print(' Reading object names for {} Fits files ...'.format(nfiles))
216         obj_ids = []
217         for a, name in enumerate(files):
218             display.progress(a, nfiles)
219             obj_ids.append( Header(name, 'object') )
220
221         display.complete()
222
223     else: obj_ids = [ Header(name, 'object') for name in files ]
224
225     if verbose:
226         # query for 'attribute' iteratively
227         print(' Searching for {}'s with SIMBAD ...'.format(attribute))
228         results = []
229         for a, obj in enumerate(obj_ids):
230             display.progress(a, nfiles)
231             results.append( SimbadSearch[attribute](obj) )
232
233         display.complete()
234
235     else: results = [ SimbadSearch[attribute](obj) for obj in obj_ids ]
236
237     if is_main:
238         formatted = {
239             'Position': '{1:.2f} {1:.2f}',
240             'Distance': '{0:.2f}',
241             'Sptype' : '{}'}
242
243         for item in results:
244             if type(item) is list:
245                 print( formatted[attribute].format(*item))
246             else:
247                 print( formatted[attribute].format(item))
248
249     else: return results
250
251 except OptionsError as err:
252     print(' --> OptionsError:', err)
253     raise FitsError('Failed assignment for Search().')
254
255 except SimbadError as err:
256     print(' --> SimbadError:', err)
257     raise FitsError('Simbad failed.')
258
259 def PositionSort( center, radius, *files, **kwargs ):
260     """
261     Return a list of files from 'files' that lie in a 'radius' (in degrees)
262     from 'center', based on the 'ra' (right ascension) and 'dec' (declination).
263
264     kwargs = {
265         'ra'      : 'pos1' , # header element for right ascension
266         'dec'     : 'pos2' , # header element for declination
267         'obj'     : 'object', # header element for object id
268         'raconvert': True , # convert decimal hours to decimal degrees
269         'verbose' : True , # display messages, progress
270         'toplevel': '' , # 'toplevel' directory to look for files in
271         'recursive': False , # search 'recursive'ly below 'toplevel'
272         'pattern' : '*.fits', # glob 'pattern' for file search
273         'useSimbad': False , # use Simbad instead of header elements
274     }

```

```

275     """
276     try:
277         # function parameter defaults
278         options = Options( kwargs,
279             {
280                 'ra'       : 'pos1' , # header element for right ascension
281                 'dec'      : 'pos2' , # header element for declination
282                 'obj'      : 'object' , # header element for object id
283                 'raconvert': True    , # convert decimal hours to decimal degrees
284                 'verbose'  : True    , # display messages, progress
285                 'toplevel' : ''      , # 'toplevel' directory for file search
286                 'recursive': False   , # search 'recursive'ly below 'toplevel'
287                 'pattern'  : '*.fits' , # glob 'pattern' for file search
288                 'useSimbad': False    # use Simbad instead of header elements
289             })
290
291         # function parameter assignments
292         ra       = options('ra')
293         dec      = options('dec')
294         obj      = options('obj')
295         raconvert = options('raconvert')
296         verbose  = options('verbose')
297         topLevel = options('toplevel')
298         recursive = options('recursive')
299         pattern  = options('pattern')
300         useSimbad = options('useSimbad')
301
302     except OptionsError as err:
303         print(' --> OptionsError:', err)
304         raise FitsError('Failed keyword assignment in PositionSort().')
305
306     # check arguments
307     if not hasattr( center, '__iter__'):
308         raise FitsError('PositionSort() expects 'center' argument to be '
309         'iterable' and have two elements.')
310     if len(center) != 2:
311         raise FitsError('PositionSort() expects 'center' argument to have '
312         'exactly two elements.')
313     if not isinstance( radius, Number ):
314         raise FitsError('PositionSort() expects 'radius' argument to '
315         'be a 'Number'.')
316     for a, f in enumerate(files):
317         if not isinstance(f, str):
318             raise FitsError('PositionSort() expects 'str' like arguments '
319             'for all 'files' (from argument {}).format(a))
320
321     # convert 'files' to list type
322     files = list(files)
323
324     # look under 'toplevel' if requested
325     if topLevel:
326         find = RFind if recursive else Find
327         files += find(topLevel, pattern)
328
329     if verbose:
330         # create display object
331         display = Monitor()
332         nfiles = len(files)
333
334     # initialize blank lists
335     pos1, pos2 = [], []
336
337     if not useSimbad:
338         if verbose: print(' Retrieving position information from {} files ... '.format(nfiles))
339         # check file headers for requested information
340         for a, fitsfile in enumerate(files):
341             try:
342                 alpha = Header(fitsfile, ra)
343                 delta = Header(fitsfile, dec)
344                 if raconvert: alpha *= 180 / 12
345                 pos1.append(alpha)
346                 pos2.append(delta)
347             except FitsError as err:
348                 # attempt to get info from SIMBAD instead
349                 print('\n Failed to retrieve position from file {}, contacted SIMBAD ...'.format(a))
350                 pos = Position( Header(fitsfile, obj) )
351                 print('\033[A\r\033[K\033[2A')
352                 pos1.append( pos[0] )
353                 pos2.append( pos[1] )
354
355                 if verbose: display.progress(a + 1, nfiles)
356
357     else:
358         # use the Simbad module to search for positions
359         if verbose: print(' Retrieving {} positions from SIMBAD ... '.format(nfiles))
360         for a, fitsfile in enumerate(files):
361             pos = Position( Header(fitsfile, obj) )
362             pos1.append( pos[0] )
363             pos2.append( pos[1] )
364             if verbose: display.progress(a, nfiles)
365
366     # erase progress bar

```

```

367     if verbose:
368         display.complete()
369         print('\r\033[K Compiling list of files ... ')
370
371     # keep files for targets within range
372     keepers = [ f for p1, p2, f in zip(pos1, pos2, files)
373                 if abs(p1 - center[0]) < radius and abs(p2 - center[1]) < radius ]
374
375     # account for p1 ~ 0 && center ~ 360 like comparisons
376     keepers += [ f for p1, p2, f in zip(pos1, pos2, files)
377                 if abs(p1 + 360 - center[0]) < radius and abs(p2 - center[1]) < radius ]
378
379     # account for p1 ~ 360 && center ~ 0 like comparisons
380     keepers += [ f for p1, p2, f in zip(pos1, pos2, files)
381                 if abs(p1 - center[0] - 360) < radius and abs(p2 - center[1]) < radius ]
382
383     if verbose: print('\033[A\r\033[K Compiling list of files ... done')
384
385     # exclude any potential double countings
386     return list(set(keepers))
387
388 def Main( clargs ):
389     """
390     Main function. See __doc__ for details.
391     """
392
393     if len(clargs) < 2:
394         # show usage
395         print( __doc__ )
396         return 0
397
398     # Available functions for execution
399     executable = {
400         'Header' : Header, # Header function
401         'Search' : Search # Search function
402     }
403
404     try:
405
406         # Parse command line arguments
407         function, args, kwargs = Parse( clargs[1:] )
408         if not args and not kwargs:
409             # show function usage
410             print( executable[function].__doc__ )
411             return 0
412
413         # run execution
414         executable[function]( *args, is_main=True, **kwargs )
415         return 0
416
417     except CommandError as err:
418         print(' --> CommandError:', err)
419         return 1
420
421     except KeyError as key:
422         print(' --> {} was not a recognized function.'.format(key))
423         return 1
424
425     except FitsError as err:
426         # don't let uncaught self exception pass if from main.
427         print(' --> FitsError:', err.msg)
428         return 1
429
430     except Exception as err:
431         print(' --> Unrecognized error from Fits module.')
432         print(' --> Exception: {}'.format(err))
433         return 1
434
435 if __name__ == '__main__':
436     # call Main function, exit 0 or 1
437     sys.exit( Main(sys.argv) )

```

C.13 .. SLiPy . Montage

```
1  # Copyright (c) Geoffrey Lentner 2015. All Rights Reserved.
2  # See LICENSE (GPLv3)
3  # slipy/SLiPy/Montage.py
4  """
5  This module makes use of the 'Montage' mosaic tools from caltech, see:
6  http://montage.ipac.caltech.edu/
7
8  The user should have Montage's executables available on their path.
9  """
10
11 import os, shutil as sh, numpy as np
12 from subprocess import check_output as call, CalledProcessError
13 from sys import stdout
14 from numbers import Number
15
16 from .. import SlipyError
17 from ..Framework.Options import Options, OptionsError
18 from ..Framework.Display import Monitor, DisplayError
19
20
21 class MontageError(SlipyError):
22     """
23     Exception specific to the Montage module
24     """
25     pass
26
27 def SolveGrid( sides, grid ):
28     """
29     SolveGrid( sides, grid ):
30
31     Helper function for the Field and SubField classes. Both 'sides' and 'grid'
32     need to be array-like and of length two. 'sides' is the side length of the
33     field in decimal degrees in right ascension and declination respectively.
34     'grid' specifies the subdivision along these axis (e.g., (2,2) says 2x2).
35
36     The user should be mindful of their choices. If the side lengths cannot be
37     subdivided into well-behaved (rational) segments, higher decimal places
38     will be lost in the SubField.ArchiveList() task resulting in small
39     gaps in the mosaic.
40     """
41     # check arguments
42     if not hasattr(sides, '__iter__') or not hasattr(grid, '__iter__'):
43         raise MontageError('Grid() expects both arguments to be array-like.')
44     if len(sides) != 2 or len(grid) != 2:
45         raise MontageError('Grid() expects both arguments to have length two.')
46
47     # grid 'site' centers in the horizontal axis
48     ra_left_site = -sides[0] / 2 + 0.5 * sides[0] / grid[0]
49     ra_right_site = sides[0] / 2 - 0.5 * sides[0] / grid[0]
50     ra_site_centers = np.linspace( ra_left_site, ra_right_site, grid[0] )
51
52     # grid 'site' centers in the vertical axis
53     dec_bottom_site = -sides[1] / 2 + 0.5 * sides[1] / grid[1]
54     dec_top_site = sides[1] / 2 - 0.5 * sides[1] / grid[1]
55     dec_site_centers = np.linspace( dec_bottom_site, dec_top_site, grid[1] )
56
57     return ra_site_centers, dec_site_centers
58
59 def Mosaic(resolution, *folders, **kwargs):
60     """
61     Mosaic(resolution, *folders, **kwargs):
62
63     Conduct standard build procedures for all 'folders'. 'resolution' is the
64     number of pixels per degree for the output image. Note: 'folders' should
65     be absolute paths.
66
67     kwargs = {
68         verbose : True, # display messages, progress
69         bkmodel : True # model and correct for background effects
70     }
71     """
72     try:
73         # function parameter defaults
74         options = Options( kwargs,
75             {
76                 'verbose': True, # display messages, progress
77                 'bkmodel': True # model and correct for background effects
78             }
79         )
80
81         # function parameter assignments
82         verbose = options('verbose')
83         bkmodel = options('bkmodel')
84
85         # build mosaics at all sites
86         for a, folder in enumerate(folders):
87             # change directories
88             os.chdir(folder)
89
```

```

90 # display message
91 if verbose:
92     stdout.write('\n Building mosaic for {}: {} / {} ... \n'
93                 .format(os.path.basename(folder), a + 1, len(folders)))
94     stdout.write(' ' + '-' * 70 + '\n')
95     stdout.write(' Generating image meta-data table ... ')
96     stdout.flush()
97
98 # generate image meta-data table
99 output = call(['mimgtbl', 'images', 'images.tbl']).decode('utf-8')
100 if 'ERROR' in output: raise MontageError('Failed 'mimgtbl' from {}'.format(folder))
101
102 if verbose:
103     stdout.write('done.\n Generating FITS header template ... ')
104     stdout.flush()
105
106 # create mosaic FITS header template
107 output = call(['mMakeHdr', '-p', '{}'.format(1 / resolution),
108               '-n', 'images.tbl', 'template.hdr']).decode('utf-8')
109 if 'ERROR' in output: raise MontageError('Failed 'mMakeHdr' from {}'.format(folder))
110
111 if verbose:
112     stdout.write('done.\n Reprojecting images ... ')
113     stdout.flush()
114
115 # reproject images
116 output = call(['mProjExec', '-p', 'images', 'images.tbl',
117               'template.hdr', 'projected', 'stats.tbl']).decode('utf-8')
118 if 'ERROR' in output: raise MontageError('Failed 'mProjExec' in {}'.format(folder))
119
120 if verbose:
121     stdout.write('done.\n Generating new image meta-data table '
122                 'for projected images ... ')
123     stdout.flush()
124
125 # create new meta-data table for reprojected images
126 output = call(['mimgtbl', 'projected', 'proj-images.tbl'
127               ]).decode('utf-8')
128 if 'ERROR' in output: raise MontageError('Failed 'mimgtbl' in {}'.format(folder))
129
130 if not bkmodel:
131     # simply co-add images
132     if verbose:
133         stdout.write('done.\n Co-adding images ... ')
134         stdout.flush()
135     output = call(['mAdd', '-p', 'projected', 'proj-images.tbl',
136                   'template.hdr', 'final/mosaic.fits']).decode('utf-8')
137     if 'ERROR' in output: raise MontageError('Failed 'mAdd' in {}'.format(folder))
138
139 else:
140     # Fit overlaps for background corrections
141     if verbose:
142         stdout.write('done.\n Fitting overlaps for background '
143                     'corrections ... ')
144         stdout.flush()
145     output = call(['mOverlaps', 'proj-images.tbl', 'diffs.tbl'
146                   ]).decode('utf-8')
147     if 'ERROR' in output: raise MontageError('Failed 'mOverlaps' in {}'.format(folder))
148
149     # perform background subtractions on overlaps
150     if verbose:
151         stdout.write('done.\n Performing background subtractions '
152                     'on overlaps ... ')
153         stdout.flush()
154     output = call(['mDiffExec', '-p', 'projected', 'diffs.tbl',
155                   'template.hdr', 'differences']).decode('utf-8')
156     if 'ERROR' in output: raise MontageError('Failed 'mDiffExec' in {}'.format(folder))
157
158     # computing plane-fitting coefficients
159     if verbose:
160         stdout.write('done.\n Computing plane-fitting coefficients ... ')
161         stdout.flush()
162     output = call(['mFitExec', 'diffs.tbl', 'fits.tbl',
163                   'differences']).decode('utf-8')
164     if 'ERROR' in output: raise MontageError('Failed 'mFitExec' in {}'.format(folder))
165
166     # create table of background corrections
167     if verbose:
168         stdout.write('done.\n Creating table of background '
169                     'corrections ... ')
170         stdout.flush()
171     output = call(['mBgModel', 'proj-images.tbl', 'fits.tbl',
172                   'corrections.tbl']).decode('utf-8')
173     if 'ERROR' in output: raise MontageError('Failed 'mBgModel' in '

```

```

182         '{}'.format(folder))
183
184     # apply background matching to reprojected images
185     if verbose:
186         stdout.write('done\n Applying background matching to '
187                     'reprojected images ... ')
188         stdout.flush()
189     output = call(['mBgExec', '-p', 'projected', 'proj-images.tbl',
190                  'corrections.tbl', 'corrected']).decode('utf-8')
191     if 'ERROR' in output: raise MontageError('Failed 'mBgExec' in '
192         '{}'.format(folder))
193
194     # co-add images for final mosaic
195     if verbose:
196         stdout.write('done\n Co-adding corrected images ... ')
197         stdout.flush()
198     output = call(['mAdd', '-p', 'corrected', 'proj-images.tbl',
199                  'template.hdr', 'final/mosaic.fits']).decode('utf-8')
200     if 'ERROR' in output: raise MontageError('Failed 'mAdd' in '
201         '{}'.format(folder))
202
203     # finished mosaic
204     if verbose:
205         stdout.write('done\n')
206         stdout.flush()
207
208     except CalledProcessError as err:
209         print(' --> CalledProcessError:', err)
210         raise MontageError('Failed process from Mosaic().')
211
212 class SubField:
213     """
214     SubField( center, sides, grid, **kwargs ):
215     """
216     def __init__(self, center, sides, grid, **kwargs):
217         """
218         Create 'site' grid for SubField.
219         """
220         try:
221             # function parameter defaults
222             options = Options( kwargs,
223                               {
224                                   'survey': 'DSS', # DSS, SDSS, 2MASS
225                                   'band' : 'DSS2B', # filter for 'survey', see 'bands' dict
226                                   'pad' : 0.0 # amount to add (degrees) around 'sites'
227                               })
228
229             # function parameter assignments
230             survey = options('survey').upper()
231             band = options('band').upper()
232             pad = options('pad')
233
234             # available bands for each survey
235             bands = {
236                 # Two-Micron All-Sky Survey
237                 '2MASS': ['J', 'H', 'K'],
238
239                 # Sloan Digital Sky Survey
240                 'SDSS': ['U', 'G', 'R', 'I', 'Z'],
241
242                 # STScI Digitized Sky Survey
243                 'DSS': ['DSS1B', 'DSS1R', 'DSS2B', 'DSS2R', 'DSS2IR', 'Quick-V']
244             }
245
246             # check for appropriate survey, band
247             if survey not in bands:
248                 raise MontageError('{}' was not a recognized survey for '
249                     'the Montage Python module.'.format(survey))
250             if band not in bands[survey]:
251                 raise MontageError('{}' was not a recognized filter band '
252                     'for the '{}' survey.'.format(band, survey))
253
254             # check arguments
255             if ( not hasattr(center, '__iter__') or
256                 not hasattr(sides, '__iter__') or not hasattr(grid, '__iter__') ):
257                 raise MontageError('SubField() expects array-like arguments for '
258                     'center', 'sides', and 'grid' arguments.')
259             if len(center) != 2 or len(sides) != 2 or len(grid) != 2:
260                 raise MontageError('SubField() expects 'center', 'sides' and '
261                     'grid' arguments to have length two.')
262
263             # SolveGrid()
264             ra_site_centers, dec_site_centers = SolveGrid(sides, grid)
265             # relative to SubField 'center':
266             ra_site_centers += center[0]
267             dec_site_centers += center[1]
268
269             # record number of 'site's along each axis
270             self.num_ra_sites = grid[0]
271             self.num_dec_sites = grid[1]
272
273             # build arguments for subprocess call

```



```

274 self.archive_command_list = [
275     ['mArchiveList', survey, band, '{:.2f} {:.2f}'.format(ra_site,
276     dec_site), str(pad + sides[0]/grid[0]),
277     str(pad + sides[1]/grid[1]), 'remote.tbl']
278     for ra_site in ra_site_centers for dec_site in dec_site_centers
279 ]
280
281 # make current directory 'home'
282 self.location = os.path.abspath('.')
283
284 # new tree structure
285 self.folders = [os.path.join(self.location, 'Site-{:03d}'.format(a+1))
286     for a in range(len(self.archive_command_list)) ]
287
288 # initialize folder structure with 'images' directory
289 for folder in self.folders:
290     abspath = os.path.join(folder, 'images')
291     if not os.path.exists(abspath):
292         os.makedirs(abspath)
293
294 except OptionsError as err:
295     print(' --> OptionsError:', err)
296     raise MontageError('Failed keyword assignment in SubField().')
297
298 def ArchiveList(self, **kwargs):
299     """
300     Run the 'mArchiveList' command on the 'site' grid.
301     """
302     try:
303         # function parameter defaults
304         options = Options( kwargs,
305             {
306                 'verbose': True # display messages, progress
307             })
308
309         # function parameter assignments
310         verbose = options('verbose')
311
312         for a, command in enumerate(self.archive_command_list):
313
314             # navigate to 'images' directory
315             os.chdir( os.path.join(self.folders[a], 'images') )
316
317             if verbose:
318                 stdout.write('\n Running 'mArchiveList' on {} ... '.format(
319                     os.path.basename(self.folders[a])))
320                 stdout.flush()
321
322             # run 'mArchiveList'
323             output = call(command).decode('utf-8')
324             if 'ERROR' in output or 'count="0"' in output:
325                 raise MontageError('Failed archive list from archive() '
326                     '(command: {}), (output: {})).format(command, output))
327
328             if verbose: stdout.write('done')
329
330         if verbose:
331             stdout.write('\n')
332             stdout.flush()
333
334     except OptionsError as err:
335         print(' --> OptionsError:', err)
336         raise MontageError('Failed keyword assigned from SubField.exec().')
337
338     except CalledProcessError as err:
339         print(' --> CalledProcessError:', err)
340         raise MontageError('mArchiveList' returned exit status 1.')
341
342 def ArchiveExec(self, **kwargs):
343     """
344     Run 'mArchiveExec' on each 'site' in the SubField.
345     """
346     try:
347         # function parameter defaults
348         options = Options( kwargs,
349             {
350                 'verbose': True # display messages, progress
351             })
352
353         # function parameter assignments
354         verbose = options('verbose')
355
356         for a, folder in enumerate(self.folders):
357
358             # navigate to site folder
359             os.chdir( os.path.join(folder, 'images') )
360
361             if verbose:
362                 stdout.write('\n Running 'mArchiveExec' on {} ... '.format(
363                     os.path.basename(folder)))
364                 stdout.flush()
365
366             # run 'mArchiveExec'

```

```

367         output = call(['mArchiveExec','remote.tbl']).decode('utf-8')
368         if 'ERROR' in output: raise MontageError('Failed 'mArchiveExec' '
369             'in folder {}'.format(folder, output))
370
371         if verbose: stdout.write('done')
372
373         if verbose:
374             stdout.write('\n')
375             stdout.flush()
376
377     except OptionsError as err:
378         print(' --> OptionsError:', err)
379         raise MontageError('Failed keyword assignment in ArchiveExec().')
380
381     except CalledProcessError as err:
382         print(' --> CalledProcessError:', err)
383         raise MontageError('mArchiveExec returned exit status 1.')
384
385 def Build(self, resolution, **kwargs):
386     """
387     Run the build process for the 'sites' in this SubField. See the
388     Montage.Mosaic() function documentation.
389     """
390     try:
391         # function parameter options
392         options = Options( kwargs,
393             {
394                 'verbose':True, # display message, progress
395                 'bkmodel':True # run background modelling procedure
396             })
397
398         # function parameter assignments
399         verbose = options('verbose')
400         bkmodel = options('bkmodel')
401
402     except OptionsError as err:
403         print(' --> OptionsError:', err)
404         raise MontageError('Failed keyword assignment in SubField.Build().')
405
406     if verbose:
407         stdout.write(' Setting up folder structure ... ')
408         stdout.flush()
409
410     # setup folder structure
411     for subdir in ['corrected','projected','differences','final']:
412         for folder in self.folders:
413             abspath = os.path.join(folder,subdir)
414             if not os.path.exists(abspath):
415                 os.makedirs(abspath)
416
417     if verbose:
418         stdout.write('done\n')
419         stdout.flush()
420
421     # run Mosaic() on all 'site's
422     Mosaic( resolution, *self.folders, verbose=verbose, bkmodel=bkmodel )
423
424 def Collect(self, **kwargs):
425     """
426     Collect( **kwargs ):
427
428     Collect the mosaics from all 'site' locations into a master 'images'
429     folder. The only 'kwarg' is 'verbose' (default: True).
430     """
431     try:
432
433         # function parameter defaults
434         options = Options( kwargs,
435             {
436                 'verbose': True # display messages, progress
437             })
438
439         # function parameter assignments
440         verbose = options('verbose')
441
442     except OptionsError as err:
443         print(' --> OptionsError:', err)
444         raise MontageError('Failed keyword assignment in SubField.Collect().')
445
446     # change to SubField 'location' directory
447     os.chdir(self.location)
448
449     # check that we have a finished mosaic at each 'site'
450     for folder in self.folders:
451         if not os.path.exists( os.path.join(folder, 'final/mosaic.fits') ):
452             raise MontageError('No 'mosaic.fits' file in {}'.format(folder))
453
454     # ensure path to master/images/
455     master_images = os.path.join(self.location, 'master/images')
456     if not os.path.exists(master_images):
457         os.makedirs(master_images)
458
459     for a, folder in enumerate(self.folders):

```

```

460
461     if verbose:
462         stdout.write('\n Copying image from {} ... '.format(
463             os.path.basename(folder)))
464         stdout.flush()
465
466     # Copy over image
467     sh.copy( os.path.join(folder, 'final/mosaic.fits'), os.path.join(
468         master_images, 'mosaic-{}.fits'.format(a + 1)) )
469
470     if verbose: stdout.write('done')
471
472 if verbose:
473     stdout.write('\n')
474     stdout.flush()
475
476 def Merge(self, resolution, **kwargs):
477     """
478     Merge(resolution, **kwargs ):
479
480     Merge all 'site' mosaics into a single master SubField mosaic. The only
481     keyword options are 'verbose' (default: True) and 'bkmodel' (default:
482     True). See Montage.Mosaic().
483     """
484     try:
485
486         # function parameter defaults
487         options = Options( kwargs,
488             {
489                 'verbose': True, # display messages, progress
490                 'bkmodel': True # model and correct for background effects
491             })
492
493         # function parameter assignments
494         verbose = options('verbose')
495         bkmodel = options('bkmodel')
496
497     except OptionsError as err:
498         print(' -> OptionsError:', err)
499         raise MontageError('Failed keyword assignment in SubField.Merge().')
500
501     # check for master directory
502     master_dir = os.path.join(self.location, 'master')
503     if not os.path.exists(master_dir):
504         raise MontageError('No 'master' directory detected for SubField '
505             '{}'.format(self.location))
506
507     # change directories
508     os.chdir(master_dir)
509
510     # create folder structure
511     for subdir in ['corrected', 'projected', 'differences', 'final']:
512         path = os.path.join(master_dir, subdir)
513         if not os.path.exists(path):
514             os.makedirs(path)
515
516     # run Mosaic on 'site' mosaics
517     Mosaic(resolution, '.', verbose=verbose, bkmodel=bkmodel)
518
519 class Field:
520     """
521     Mosaic manager for 'Montage'.
522     """
523     def __init__(self, center, sides, grid, subgrid, **kwargs):
524         """
525         Initialize a Field centered on 'center' (array-like of length two with
526         right ascension and declination in decimal degrees) and side lengths
527         'sides' (array-like of length two in units of decimal degrees in
528         right ascension and declination respectively). 'grid' (array-like of
529         length two) specifies the grid layout (e.g., (4,4) says 4x4) to
530         subdivide the Field. The 'subgrid' is the same but pertaining to the
531         further subdivision of each SubField into a grid layout of 'sites'.
532         See SubField class.
533
534         kwargs = {
535             'verbose': True, # display message, progress
536             'survey': 'DSS', # 2MASS, SDSS, DSS
537             'band': 'DSS2B' # filter 'band' pertaining to 'survey'
538         }
539         """
540     try:
541         # function parameter defaults
542         options = Options( kwargs,
543             {
544                 'verbose': True, # display message, progress
545                 'survey': 'DSS', # 2MASS, SDSS, DSS
546                 'band': 'DSS2B' # filter 'band' pertaining to 'survey'
547             })
548
549         # function parameter assignments
550         verbose = options('verbose')
551         survey = options('survey')
552         band = options('band')

```

```

553
554 except OptionsError as err:
555     print(' --> OptionsError:', err)
556     raise MontageError('Failed keyword assignment in Field().')
557
558 # available bands for each survey
559 bands = {
560     # Two-Micron All-Sky Survey
561     '2MASS': ['J', 'H', 'K'],
562
563     # Sloan Digital Sky Survey
564     'SDSS': ['U', 'G', 'R', 'I', 'Z'],
565
566     # STScI Digitized Sky Survey
567     'DSS': ['DSS1B', 'DSS1R', 'DSS2B', 'DSS2R', 'DSS2IR', 'Quick-V']
568 }
569
570 # check for appropriate survey, band
571 if survey not in bands:
572     raise MontageError('{} was not a recognized survey for '
573         'the Montage Python module.'.format(survey))
574 if band not in bands[survey]:
575     raise MontageError('{} was not a recognized filter band '
576         'for the {} survey.'.format(band, survey))
577
578 # check arguments
579 if ( not hasattr(center, '__iter__') or
580     not hasattr(sides, '__iter__') or not hasattr(grid, '__iter__') or
581     not hasattr(subgrid, '__iter__')):
582     raise MontageError('Field() expects array-like arguments.')
583 if ( len(center) != 2 or len(sides) != 2 or len(grid) != 2 or
584     len(subgrid) != 2 ):
585     raise MontageError('Field() expects arguments to be length two.')
586
587 if verbose:
588     stdout.write('\n Setting up {:d}x{:d} Field around ({:.2f}, '
589         '{:.2f}) ... '.format(grid[0], grid[1], center[0], center[1]))
590     stdout.flush()
591
592 # SolveGrid()
593 self.ra_centers, self.dec_centers = SolveGrid(sides, grid)
594 # relative to Field 'center':
595 self.ra_centers += center[0]
596 self.dec_centers += center[1]
597
598 # side lengths for SubField's
599 self.sub_sides = ( sides[0] / grid[0], sides[1] / grid[1] )
600
601 # set current directory to 'Field directory'.
602 self.location = os.path.abspath('.')
603
604 # name SubField directories
605 self.folders = [os.path.join(self.location, 'SubField-{:03d}'.format(a+1))
606     for a in range(len(self.ra_centers) * len(self.dec_centers)) ]
607
608 # create SubField directories
609 for folder in self.folders:
610     if not os.path.exists(folder):
611         os.makedirs(folder)
612
613 # zip together all ra, dec pairs
614 self.sub_centers = [ (ra, dec)
615     for ra in self.ra_centers for dec in self.dec_centers ]
616
617 # initialize empty list of SubField's
618 self.subfields = []
619
620 # initialize all SubField's
621 for a, folder, sub_center in zip(range(len(self.folders)), self.folders,
622     self.sub_centers):
623
624     if verbose:
625         stdout.write('\n Initializing {} ... '.format(
626             os.path.basename(folder)))
627         stdout.flush()
628
629     # change directories
630     os.chdir(folder)
631
632     # create SubField
633     self.subfields.append( SubField(sub_center, self.sub_sides,
634         subgrid, survey = survey, band = band) )
635
636     if verbose: stdout.write('done')
637
638 if verbose:
639     stdout.write('\n')
640     stdout.flush()
641
642 def ArchiveList(self, **kwargs):
643     """
644     Run 'ArchiveList()' on all SubFields. The only keyword option is

```

```

645     'verbose' (default: True).
646     """
647     try:
648         # function parameter defaults
649         options = Options( kwargs,
650                             {
651                                 'verbose': True # display messages, progress
652                             })
653
654         # function parameter assignments
655         verbose = options('verbose')
656
657     except OptionsError as err:
658         print(' --> OptionsError:', err)
659         raise MontageError('Failed keyword assignment in '
660                             'Field.ArchiveList().')
661
662     if verbose:
663         stdout.write('\n Running ArchiveList() on all SubFields ... ')
664         stdout.write('\n ' + '-' * 70 + '\n')
665         stdout.flush()
666
667     # Run ArchiveList() on all SubField's
668     for a, subfield in enumerate(self.subfields):
669
670         if verbose:
671             stdout.write('\n Running ArchiveList() on {} ... '.
672                           .format(os.path.basename(self.folders[a])))
673             stdout.flush()
674
675         # run ArchiveList()
676         subfield.ArchiveList(verbose = False)
677
678         if verbose: stdout.write('done')
679
680     if verbose:
681         stdout.write('\n')
682         stdout.flush()
683
684     def ArchiveExec(self, **kwargs):
685         """
686         Run 'ArchiveExec()' on all SubFields. The only keyword option is
687         'verbose' (default: True).
688         """
689         try:
690             # function parameter defaults
691             options = Options( kwargs,
692                                 {
693                                     'verbose': True # display messages, progress
694                                 })
695
696             # function parameter assignments
697             verbose = options('verbose')
698
699         except OptionsError as err:
700             print(' --> OptionsError:', err)
701             raise MontageError('Failed keyword assignment in '
702                                 'Field.ArchiveExec().')
703
704         if verbose:
705             stdout.write('\n Running ArchiveExec() on all SubFields ... ')
706             stdout.write('\n ' + '-' * 70 + '\n')
707             stdout.flush()
708
709         # Run ArchiveExec() on all SubField's
710         for a, subfield in enumerate(self.subfields):
711
712             if verbose:
713                 stdout.write('\n Running ArchiveExec() on {}: {} / {} ... '.
714                               .format(os.path.basename(self.folders[a]), a + 1,
715                                       len(self.folders)))
716                 stdout.flush()
717
718             # run ArchiveList()
719             subfield.ArchiveExec(verbose = False)
720
721             if verbose: stdout.write('done')
722
723         if verbose:
724             stdout.write('\n')
725             stdout.flush()
726
727     def Build(self, resolution, **kwargs):
728         """
729         Build(resolution, **kwargs):
730
731         Run the build process for all SubFields in this Field. See the
732         documentation for Montage.Mosaic() and SubField.Build().
733
734         kwargs = {
735             'verbose': True, # display messages, progress
736             'bkmodel': True # run background modelling procedures.
737         }

```

```

738 """
739 try:
740     # function parameter defaults
741     options = Options( kwargs,
742         {
743             'verbose': True, # display messages, progress
744             'bkmodel': True # run background modelling procedure
745         })
746
747     # function parameter assignments
748     verbose = options('verbose')
749     bkmodel = options('bkmodel')
750
751 except OptionsError as err:
752     print(' --> OptionsError:', err)
753     raise MontageError('Failed keyword assignment in '
754         'Field.ArchiveExec().')
755
756 if verbose:
757     stdout.write('\n Running Build() on all SubField's ... ')
758     stdout.write('\n' + '=' * 70 + '\n')
759     stdout.write('      '=' * 70 + '\n')
760     stdout.flush()
761
762 # Run ArchiveExec() on all SubField's
763 for a, subfield in enumerate(self.subfields):
764
765     if verbose:
766         stdout.write('\n Running Build() on {}: {} / {} ... '
767             .format(os.path.basename(self.folders[a]), a + 1,
768                 len(self.folders)))
769         stdout.write('\n' + '=' * 70 + '\n')
770         stdout.flush()
771
772     # run ArchiveList()
773     subfield.Build(verbose = verbose, bkmodel = bkmodel)
774
775     if verbose:
776         stdout.write('\n')
777         stdout.flush()
778
779 def Collect(self, **kwargs):
780     """
781     Run Collect() on all SubFields of this Field.
782     """
783     try:
784         # function parameter defaults
785         options = Options( kwargs,
786             {
787                 'verbose': True, # display messages, progress
788             })
789
790         # function parameter assignments
791         verbose = options('verbose')
792
793     except OptionsError as err:
794         print(' --> OptionsError:', err)
795         raise MontageError('Failed keyword assignment in '
796             'Field.ArchiveExec().')
797
798     if verbose:
799         stdout.write('\n Running Collect() on all SubField's ... ')
800         stdout.write('\n' + '=' * 70 + '\n')
801         stdout.write('      '=' * 70 + '\n')
802         stdout.flush()
803
804     # Run ArchiveExec() on all SubField's
805     for a, subfield in enumerate(self.subfields):
806
807         if verbose:
808             stdout.write('\n Running Collect() on {}: {} / {} ... '
809                 .format(os.path.basename(self.folders[a]), a + 1,
810                     len(self.folders)))
811             stdout.write('\n' + '=' * 70 + '\n')
812             stdout.flush()
813
814         # run ArchiveList()
815         subfield.Collect( verbose=verbose )
816
817         if verbose:
818             stdout.write('\n')
819             stdout.flush()
820
821 def Merge(self, resolution, **kwargs):
822     """
823     Merge(resolution, **kwargs):
824
825     Run Merge() on all SubFields of this Field. See SubField.Merge().
826     """
827     try:
828         # function parameter defaults
829         options = Options( kwargs,
830             {

```

```

831         'verbose': True, # display messages, progress
832     })
833
834     # function parameter assignments
835     verbose = options('verbose')
836
837     except OptionsError as err:
838         print(' --> OptionsError:', err)
839         raise MontageError('Failed keyword assignment in '
840                             'Field.ArchiveExec().')
841
842     if verbose:
843         stdout.write('\n Running Merge() on all SubField's ... ')
844         stdout.write('\n' + '=' * 70 + '\n')
845         stdout.write('      '=' * 70 + '\n')
846         stdout.flush()
847
848     # Run ArchiveExec() on all SubField's
849     for a, subfield in enumerate(self.subfields):
850
851         if verbose:
852             stdout.write('\n Running Merge() on {}: {} / {} ... '
853                         .format(os.path.basename(self.folders[a]), a + 1,
854                                 len(self.folders)))
855             stdout.write('\n' + '=' * 70 + '\n')
856             stdout.flush()
857
858         # run ArchiveList()
859         subfield.Merge( verbose=verbose )
860
861     if verbose:
862         stdout.write('\n')
863         stdout.flush()
864
865     def Finalize(self, resolution, **kwargs):
866         """
867         Finalize(resolution, **kwargs):
868
869         Collect all SubField/master mosaics into a single folder and
870         run Mosaic() on them for a single final image.
871         """
872         try:
873
874             # function parameter defaults
875             options = Options( kwargs,
876                                 {
877                                     'verbose': True # display messages, progress
878                                 }
879                             )
880
881             # function parameter assignments
882             verbose = options('verbose')
883
884             except OptionsError as err:
885                 print(' --> OptionsError:', err)
886                 raise MontageError('Failed keyword assignment on Field.Finalize().')
887
888             # relocate to Field directory
889             os.chdir(self.location)
890
891             # create master directory
892             master_dir = os.path.join(self.location, 'master')
893             if not os.path.exists(master_dir):
894                 os.makedirs(master_dir)
895
896             # create master directory sub-structure
897             for subdir in ['images', 'projected', 'differences', 'corrected', 'final']:
898                 path = os.path.join(master_dir, subdir)
899                 if not os.path.exists(path):
900                     os.makedirs(path)
901
902             # collect master mosaics
903             for a, folder in enumerate(self.folders):
904
905                 if verbose:
906                     stdout.write('\n Copying image from {} ... '.format(
907                                 os.path.basename(folder)))
908                     stdout.flush()
909
910                 # SubField mosaic
911                 image = os.path.join(folder, 'master/final/mosaic.fits')
912
913                 # ensure Merge() was run
914                 if not os.path.exists(image):
915                     raise MontageError('Missing 'master' mosaic image in {}'.format(
916                                 os.path.basename(folder)))
917
918                 # copy image to Field 'master' image directory
919                 sh.copy(image, os.path.join(master_dir, 'images/mosaic-{}.fits'
920                                             .format(a + 1)))
921
922                 if verbose: stdout.write('done')
923

```

```
924     if verbose:
925         stdout.write('\n')
926         stdout.flush()
927
928     # change directories to 'master'
929     os.chdir(master_dir)
930
931     # run Mosaic() on all SubField 'master's
932     Mosaic(resolution, '.', verbose=verbose, bkmodel=bkmodel)
```

C.14 .. SLiPy . Observatory

```
1  # Copyright (c) Geoffrey Lentner 2015. All Rights Reserved.
2  # See LICENSE (GPLv3)
3  # slipy/SLiPy/Observatory.py
4  """
5  Classes for defining observatory parameters (similar to the IRAF task).
6  """
7
8  from astropy import units as u
9
10 # there is no need for an 'ObservatoryError' class ...
11
12 class Observatory:
13     """
14     The Abstract base class for Observatory types.
15     """
16     def __init__(self):
17         raise TypeError('The Observatory base class should not be '
18                         'instantiated on its own.')
19
20     def __repr__(self):
21         return str(self)
22
23     def __str__(self):
24         res = '' if not hasattr(self, 'resolution') else 'resolution = ' + str(self.resolution)
25         return ('name = {}\nlongitude = {}\nlatitude = {}\naltitude = {}\n'
26               'timezone = {}'.format(self.name, self.longitude, self.latitude,
27                                     self.altitude, self.timezone)) + res + '\n'
28
29 class OHP(Observatory):
30     """
31     The Observatoire de Haute-Provence, France.
32     """
33     def __init__(self):
34         self.name = 'Observatoire de Haute-Provence'
35         self.longitude = 356.28667 * u.degree # West
36         self.latitude = 43.9308334 * u.degree # North
37         self.altitude = 650 * u.meter
38         self.timezone = 1 * u.hourangle
39         self.resolution = 42000 * u.dimensionless_unscaled
40
41 #
42 # All of the below observatory parameters have been taken directly from IRAF!
43 #
44
45 class KPNO(Observatory):
46     """
47     Kitt Peak National Observatory
48     """
49     def __init__(self):
50         self.name = "Kitt Peak National Observatory"
51         self.longitude = 111.6 * u.degree # West
52         self.latitude = 31.9633333333 * u.degree # North
53         self.altitude = 2120. * u.meter
54         self.timezone = 7 * u.hourangle
55
56 class WIYN(Observatory):
57     """
58     WIYN Observatory
59     """
60     def __init__(self):
61         self.name = "WIYN Observatory"
62         self.longitude = 111.6 * u.degree # West
63         self.latitude = 31.9633333333 * u.degree # North
64         self.altitude = 2120. * u.meter
65         self.timezone = 7 * u.hourangle
66
67 class CTIO(Observatory):
68     """
69     Cerro Tololo Interamerican Observatory
70     """
71     def __init__(self):
72         self.name = "Cerro Tololo Interamerican Observatory"
73         self.longitude = 70.815 * u.degree # West
74         self.latitude = -30.16527778 * u.degree # North
75         self.altitude = 2215. * u.meter
76         self.timezone = 4 * u.hourangle
77
78 class LASILLA(Observatory):
79     """
80     European Southern Observatory: La Silla
81     """
82     def __init__(self):
83         self.name = "European Southern Observatory: La Silla."
84         self.longitude = 70.73 * u.degree # West
85         self.latitude = -28.7433333333 * u.degree # North
86         self.altitude = 2347 * u.meter
87         self.timezone = 4 * u.hourangle
88
```

```

89 class PARANAL(Observatory):
90     """
91     European Southern Observatory: Paranal
92     """
93     def __init__(self):
94         self.name = "European Southern Observatory: Paranal"
95         self.longitude = 70.4033333333 * u.degree # West
96         self.latitude = -23.375 * u.degree # North
97         self.altitude = 2635 * u.meter
98         self.timezone = 4 * u.hourangle
99
100 class LICK(Observatory):
101     """
102     Lick Observatory
103     """
104     def __init__(self):
105         self.name = "Lick Observatory"
106         self.longitude = 121.636666667 * u.degree # West
107         self.latitude = 37.3433333333 * u.degree # North
108         self.altitude = 1290 * u.meter
109         self.timezone = 8 * u.hourangle
110
111 # Observatory entry from a conversation with Craig Foltz 8/20/97.
112 # Name was changed and the "mmt" entry was removed.
113 class MMT0(Observatory):
114     """
115     MMT Observatory
116     """
117     def __init__(self):
118         self.name = "MMT Observatory"
119         self.longitude = 110.885 * u.degree # West
120         self.latitude = 31.6883333333 * u.degree # North
121         self.altitude = 2600 * u.meter
122         self.timezone = 7 * u.hourangle
123
124 class CFHT(Observatory):
125     """
126     Canada-France-Hawaii Telescope
127     """
128     def __init__(self):
129         self.name = "Canada-France-Hawaii Telescope"
130         self.longitude = 155.471666667 * u.degree # West
131         self.latitude = 19.8266666667 * u.degree # North
132         self.altitude = 4215 * u.meter
133         self.timezone = 10 * u.hourangle
134
135 class LAPALMA(Observatory):
136     """
137     Roque de los Muchachos, La Palma
138     """
139     def __init__(self):
140         self.name = "Roque de los Muchachos, La Palma."
141         self.longitude = 17.88 * u.degree # West
142         self.latitude = 28.7583333333 * u.degree # North
143         self.altitude = 2327 * u.meter
144         self.timezone = 0 * u.hourangle
145
146 class MSO(Observatory):
147     """
148     Mt. Stromlo Observatory
149     """
150     def __init__(self):
151         self.name = "Mt. Stromlo Observatory"
152         self.longitude = 210.975666667 * u.degree # West
153         self.latitude = -34.67935 * u.degree # North
154         self.altitude = 767 * u.meter
155         self.timezone = -10 * u.hourangle
156
157 class SSO(Observatory):
158     """
159     Siding Spring Observatory
160     """
161     def __init__(self):
162         self.name = "Siding Spring Observatory"
163         self.longitude = 210.938805556 * u.degree # West
164         self.latitude = -30.7266388889 * u.degree # North
165         self.altitude = 1149 * u.meter
166         self.timezone = -10 * u.hourangle
167
168 class AAO(Observatory):
169     """
170     Anglo-Australian Observatory
171     """
172     def __init__(self):
173         self.name = "Anglo-Australian Observatory"
174         self.longitude = 210.933913889 * u.degree # West
175         self.latitude = -30.7229611111 * u.degree # North
176         self.altitude = 1164 * u.meter
177         self.timezone = -10 * u.hourangle
178
179 class MCDONALD(Observatory):
180     """

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181 McDonald Observatory
182
183 def __init__(self):
184     self.name = "McDonald Observatory"
185     self.longitude = 104.0216667 * u.degree # West
186     self.latitude = 30.6716667 * u.degree # North
187     self.altitude = 2075 * u.meter
188     self.timezone = 6 * u.hourangle
189
190 class LCO(Observatory):
191
192     Las Campanas Observatory
193
194     def __init__(self):
195         self.name = "Las Campanas Observatory"
196         self.longitude = 70.701666667 * u.degree # West
197         self.latitude = -28.996666667 * u.degree # North
198         self.altitude = 2282 * u.meter
199         self.timezone = 4 * u.hourangle
200
201 # Submitted by Alan Koski 1/13/93
202 class MTBIGELOW(Observatory):
203
204     Catalina Observatory: 61 inch telescope
205
206     def __init__(self):
207         self.name = "Catalina Observatory: 61 inch telescope"
208         self.longitude = 110.731666667 * u.degree # West
209         self.latitude = 32.416666667 * u.degree # North
210         self.altitude = 2510. * u.meter
211         self.timezone = 7 * u.hourangle
212
213 # Revised by Daniel Durand 2/23/93
214 class DAO(Observatory):
215
216     Dominion Astrophysical Observatory
217
218     def __init__(self):
219         self.name = "Dominion Astrophysical Observatory"
220         self.longitude = 123.416666667 * u.degree # West
221         self.latitude = 48.521666667 * u.degree # North
222         self.altitude = 229 * u.meter
223         self.timezone = 8 * u.hourangle
224
225 # Submitted by Patrick Vielle 5/4/93
226 class SPM(Observatory):
227
228     Observatorio Astronomico Nacional, San Pedro Martir
229
230     def __init__(self):
231         self.name = "Observatorio Astronomico Nacional, San Pedro Martir."
232         self.longitude = 115.486944444 * u.degree # West
233         self.latitude = 31.029166667 * u.degree # North
234         self.altitude = 2830 * u.meter
235         self.timezone = 7 * u.hourangle
236
237 # Submitted by Patrick Vielle 5/4/93
238 class TONA(Observatory):
239
240     Observatorio Astronomico Nacional, Tonantzintla
241
242     def __init__(self):
243         self.name = "Observatorio Astronomico Nacional, Tonantzintla."
244         self.longitude = 98.313888889 * u.degree # West
245         self.latitude = 19.032777778 * u.degree # North
246         self.timezone = 8 * u.hourangle
247
248 # Submitted by Don Hamilton 8/18/93
249 class PALOMAR(Observatory):
250
251     The Hale Telescope
252
253     def __init__(self):
254         self.name = "The Hale Telescope"
255         self.longitude = 116.863 * u.degree # West
256         self.latitude = 33.356 * u.degree # North
257         self.altitude = 1706. * u.meter
258         self.timezone = 8 * u.hourangle
259
260 # Submitted by Pat Seitzer 10/31/93
261 class MDM(Observatory):
262
263     Michigan-Dartmouth-MIT Observatory
264
265     def __init__(self):
266         self.name = "Michigan-Dartmouth-MIT Observatory"
267         self.longitude = 111.616666667 * u.degree # West
268         self.latitude = 31.95 * u.degree # North
269         self.altitude = 1938.5 * u.meter
270         self.timezone = 7 * u.hourangle
271
272 # Submitted by Ignacio Ferrin 9/1/94

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273 class NOV(Observatory):
274     """
275     National Observatory of Venezuela
276     """
277     def __init__(self):
278         self.name = "National Observatory of Venezuela"
279         self.longitude = 70.866666667 * u.degree # West
280         self.latitude = 8.79 * u.degree # North
281         self.altitude = 3610 * u.meter
282         self.timezone = 4 * u.hourangle
283
284 # Submitted by Alan Welty 10/28/94
285 class BMO(Observatory):
286     """
287     Black Moshannon Observatory
288     """
289     def __init__(self):
290         self.name = "Black Moshannon Observatory"
291         self.longitude = 78.005 * u.degree # West
292         self.latitude = 40.921666667 * u.degree # North
293         self.altitude = 738 * u.meter
294         self.timezone = 5 * u.hourangle
295
296 # Submitted by Biwei JIANG 11/28/95
297 class BAO(Observatory):
298     """
299     Beijing XingLong Observatory
300     """
301     def __init__(self):
302         self.name = "Beijing XingLong Observatory"
303         self.longitude = 242.425 * u.degree # West
304         self.latitude = 40.393333333 * u.degree # North
305         self.altitude = 950. * u.meter
306         self.timezone = -8 * u.hourangle
307
308 # From Astronomical Almanac 1996
309 class KECK(Observatory):
310     """
311     W. M. Keck Observatory
312     """
313     def __init__(self):
314         self.name = "W. M. Keck Observatory"
315         self.longitude = 155.478333333 * u.degree # West
316         self.latitude = 19.828333333 * u.degree # North
317         self.altitude = 4160 * u.meter
318         self.timezone = 10 * u.hourangle
319
320 # Submitted by Lina Tomasella 6/11/96: Padova Astronomical Obs., Asiago, Italy.
321 class EKAR(Observatory):
322     """
323     Mt. Ekar 182 cm. Telescope
324     """
325     def __init__(self):
326         self.name = "Mt. Ekar 182 cm. Telescope"
327         self.longitude = 348.418866667 * u.degree # West
328         self.latitude = 45.848588889 * u.degree # North
329         self.altitude = 1413.69 * u.meter
330         self.timezone = -1 * u.hourangle
331
332 # Submitted by Michael Ledlow 8/8/96
333 class APO(Observatory):
334     """
335     Apache Point Observatory
336     """
337     def __init__(self):
338         self.name = "Apache Point Observatory"
339         self.longitude = 105.82 * u.degree # West
340         self.latitude = 32.78 * u.degree # North
341         self.altitude = 2798. * u.meter
342         self.timezone = 7 * u.hourangle
343
344 # Submitted by Michael Ledlow 8/8/96
345 class LOWELL(Observatory):
346     """
347     Lowell Observatory
348     """
349     def __init__(self):
350         self.name = "Lowell Observatory"
351         self.longitude = 111.535 * u.degree # West
352         self.latitude = 35.096666667 * u.degree # North
353         self.altitude = 2198. * u.meter
354         self.timezone = 7 * u.hourangle
355
356 # Submitted by S.G. Bhargavi 8/12/96
357 class VBO(Observatory):
358     """
359     Vainu Bappu Observatory
360     """
361     def __init__(self):
362         self.name = "Vainu Bappu Observatory"
363         self.longitude = 281.1734 * u.degree # West
364         self.latitude = 12.57666 * u.degree # North

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365         self.altitude = 725. * u.meter
366         self.timezone = -5.5 * u.hourangle
367
368 # Submitted by S. Giridhar 6/28/03
369 class IAO(Observatory):
370     """
371     Indian Astronomical Observatory, Hanle
372     """
373     def __init__(self):
374         self.name = "Indian Astronomical Observatory, Hanle"
375         self.longitude = 281.03583 * u.degree # West
376         self.latitude = 32.7794 * u.degree # North
377         self.altitude = 4500 * u.meter
378         self.timezone = -5.5 * u.hourangle
379
380 # Submitted by Doug Mink 1/6/97
381 class FLW0(Observatory):
382     """
383     Whipple Observatory
384     """
385     def __init__(self):
386         self.name = "Whipple Observatory"
387         self.longitude = 110.8775 * u.degree # West
388         self.latitude = 31.6809444444 * u.degree # North
389         self.altitude = 2320 * u.meter
390         self.timezone = 7 * u.hourangle
391
392 class FLW01(Observatory):
393     """
394     Whipple Observatory
395     """
396     def __init__(self):
397         self.name = "Whipple Observatory"
398         self.longitude = 110.8775 * u.degree # West
399         self.latitude = 31.6809444444 * u.degree # North
400         self.altitude = 2320 * u.meter
401         self.timezone = 7 * u.hourangle
402
403 # Submitted by Doug Mink 1/6/97
404 class ORO(Observatory):
405     """
406     Oak Ridge Observatory
407     """
408     def __init__(self):
409         self.name = "Oak Ridge Observatory"
410         self.longitude = 71.5581444444 * u.degree # West
411         self.latitude = 42.5052611111 * u.degree # North
412         self.altitude = 184 * u.meter
413         self.timezone = 5 * u.hourangle
414
415 # Submitted by Claudia Vilega Rodriques 12/12/97
416 class LNA(Observatory):
417     """
418     Laboratorio Nacional de Astrofisica - Brazil
419     """
420     def __init__(self):
421         self.name = "Laboratorio Nacional de Astrofisica - Brazil"
422         self.longitude = 45.5825 * u.degree # West
423         self.latitude = -21.4655555556 * u.degree # North
424         self.altitude = 1864 * u.meter
425         self.timezone = 3 * u.hourangle
426
427 # Submitted by John Memzies 12/31/99
428 class SAAO(Observatory):
429     """
430     South African Astronomical Observatory
431     """
432     def __init__(self):
433         self.name = "South African Astronomical Observatory"
434         self.longitude = 339.1893055556 * u.degree # West
435         self.latitude = -31.6205555556 * u.degree # North
436         self.altitude = 1798 * u.meter
437         self.timezone = -2 * u.hourangle
438
439 # Submitted by Jorge Federico Gonzalez 12/10/98
440 class CASLEO(Observatory):
441     """
442     Complejo Astronomico El Leoncito, San Juan
443     """
444     def __init__(self):
445         self.name = "Complejo Astronomico El Leoncito, San Juan."
446         self.longitude = 69.3 * u.degree # West
447         self.latitude = -30.2008333333 * u.degree # North
448         self.altitude = 2552 * u.meter
449         self.timezone = 3 * u.hourangle
450
451 # Submitted by Jorge Federico Gonzalez 12/10/98
452 class BOSQUE(Observatory):
453     """
454     Estacion Astrofisica Bosque Alegre, Cordoba
455     """
456     def __init__(self):

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457     self.name       = "Estacion Astrofisica Bosque Alegre, Cordoba."
458     self.longitude  = 64.5458333333 * u.degree # West
459     self.latitude   = -30.4016666667 * u.degree # North
460     self.altitude   = 1250 * u.meter
461     self.timezone   = 3 * u.hourangle
462
463 # Submitted by Ilian Iliev 1/19/99
464 class ROZHEN(Observatory):
465     """
466     National Astronomical Observatory Rozhen - Bulgaria
467     """
468     def __init__(self):
469         self.name       = "National Astronomical Observatory Rozhen - Bulgaria."
470         self.longitude  = 335.256111111 * u.degree # West
471         self.latitude   = 41.6930555556 * u.degree # North
472         self.altitude   = 1759 * u.meter
473         self.timezone   = -2 * u.hourangle
474
475 # Submitted by Bill Vacca 7/14/99
476 class IRTF(Observatory):
477     """
478     NASA Infrared Telescope Facility
479     """
480     def __init__(self):
481         self.name       = "NASA Infrared Telescope Facility"
482         self.longitude  = 155.471999 * u.degree # West
483         self.latitude   = 19.826218 * u.degree # North
484         self.altitude   = 4168 * u.meter
485         self.timezone   = 10 * u.hourangle
486
487 # Submitted by Andy Layden 7/16/99
488 class BGSUO(Observatory):
489     """
490     Bowling Green State Univ Observatory
491     """
492     def __init__(self):
493         self.name       = "Bowling Green State Univ Observatory."
494         self.longitude  = 83.6591666667 * u.degree # West
495         self.latitude   = 41.3783333333 * u.degree # North
496         self.altitude   = 225. * u.meter
497         self.timezone   = 5 * u.hourangle
498
499 # Submitted by Oliver-Mark Cordes 8/5/99
500 class DSAZ(Observatory):
501     """
502     Deutsch-Spanisches Observatorium Calar Alto - Spain
503     """
504     def __init__(self):
505         self.name       = "Deutsch-Spanisches Observatorium Calar Alto - Spain."
506         self.longitude  = 2.54625 * u.degree # West
507         self.latitude   = 37.2236111111 * u.degree # North
508         self.altitude   = 2168 * u.meter
509         self.timezone   = -1 * u.hourangle
510
511 # Submitted by Matilde Fernandez 2/2/99
512 class CA(Observatory):
513     """
514     Calar Alto Observatory
515     """
516     def __init__(self):
517         self.name       = "Calar Alto Observatory"
518         self.longitude  = 2.54625 * u.degree # West
519         self.latitude   = 37.2236111111 * u.degree # North
520         self.altitude   = 2168 * u.meter
521         self.timezone   = -1 * u.hourangle
522
523 # Submitted by Oliver-Mark Cordes 8/5/99
524 class HOLI(Observatory):
525     """
526     Observatorium Hoher List (Universitaet Bonn) - Germany
527     """
528     def __init__(self):
529         self.name       = "Observatorium Hoher List (Universitaet Bonn) - Germany."
530         self.longitude  = 6.85 * u.degree # West
531         self.latitude   = 50.16276 * u.degree # North
532         self.altitude   = 541 * u.meter
533         self.timezone   = -1 * u.hourangle
534
535 # Submitted by Steven Majewski 8/27/99
536 class LMO(Observatory):
537     """
538     Leander McCormick Observatory
539     """
540     def __init__(self):
541         self.name       = "Leander McCormick Observatory"
542         self.longitude  = 78.5233333333 * u.degree # West
543         self.latitude   = 38.0333333333 * u.degree # North
544         self.altitude   = 264 * u.meter
545         self.timezone   = 5 * u.hourangle
546
547 # Submitted by Steven Majewski 8/27/99
548 class FMO(Observatory):

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549     """
550     Fan Mountain Observatory
551     """
552     def __init__(self):
553         self.name = "Fan Mountain Observatory"
554         self.longitude = 78.693333333 * u.degree # West
555         self.latitude = 37.878333333 * u.degree # North
556         self.altitude = 566 * u.meter
557         self.timezone = 5 * u.hourangle
558
559     # Submitted by Kim K. McLeod 10/13/1999
560     class WHITIN(Observatory):
561         """
562         Whitin Observatory, Wellesley College
563         """
564         def __init__(self):
565             self.name = "Whitin Observatory, Wellesley College"
566             self.longitude = 71.305833 * u.degree # West
567             self.latitude = 42.295 * u.degree # North
568             self.altitude = 32 * u.meter
569             self.timezone = 5 * u.hourangle
570
571     # Submitted by Nuno Peixinho 6/7/2000
572     # Parameters for the Sierra Nevada Observatory (Spain)
573     class OSN(Observatory):
574         """
575         Observatorio de Sierra Nevada
576         """
577         def __init__(self):
578             self.name = "Observatorio de Sierra Nevada"
579             self.longitude = 3.384722222 * u.degree # West
580             self.latitude = 37.064166667 * u.degree # North
581             self.altitude = 2896 * u.meter
582             self.timezone = -1 * u.hourangle
583
584     # Gemini Observatory - Submitted by Inger Jorgensen
585     #
586     # Gemini-North
587     # These values are from the aerial survey made Sept 25, 1996
588     # http://www.ifa.hawaii.edu/mko/coordinates.html
589
590     class GEMININORTH(Observatory):
591         """
592         Gemini North Observatory
593         """
594         def __init__(self):
595             self.name = "Gemini North Observatory"
596             self.longitude = 155.46904675 * u.degree # West
597             self.latitude = 19.8238015 * u.degree # North
598             self.altitude = 4213.4 * u.meter
599             self.timezone = 10 * u.hourangle
600
601     # Gemini-South
602     # The coordinates are from GPS measurements and the elevation
603     # is from the Gemini Web pages http://www.gemini.edu/public
604
605     # class GEMINI-SOUTH(Observatory):
606     # """
607     # Gemini South Observatory
608     # """
609     # def __init__(self):
610     #     self.name = "Gemini South Observatory"
611     #     self.longitude = 70.723333333 * u.degree # West
612     #     self.latitude = -29.771666667 * u.degree # North
613     #     self.altitude = 2737. * u.meter
614     #     self.timezone = 4 * u.hourangle
615
616     # Corrected coords from Bryan Miller, 5/18/2006
617     class GEMINISOUTH(Observatory):
618         """
619         Gemini South Observatory
620         """
621         def __init__(self):
622             self.name = "Gemini South Observatory"
623             self.longitude = 70.736933333 * u.degree # West
624             self.latitude = -29.75925 * u.degree # North
625             self.altitude = 2722. * u.meter
626             self.timezone = 4 * u.hourangle
627
628     # ESO
629
630     class LASILLA(Observatory):
631         """
632         European Southern Observatory: La Silla
633         """
634         def __init__(self):
635             self.name = "European Southern Observatory: La Silla."
636             self.longitude = 70.73 * u.degree # West
637             self.latitude = -28.743333333 * u.degree # North
638             self.altitude = 2347 * u.meter
639             self.timezone = 4 * u.hourangle
640

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641 class PARANAL(Observatory):
642     """
643     European Southern Observatory: Paranal
644     """
645     def __init__(self):
646         self.name = "European Southern Observatory: Paranal."
647         self.longitude = 70.4033333333 * u.degree # West
648         self.latitude = -23.375 * u.degree # North
649         self.altitude = 2635 * u.meter
650         self.timezone = 4 * u.hourangle
651
652 # The following additional entries were supplied by Peter Weilbacher
653 # weilbach@uni-sw.gwdg.de on 28 Jan 2002 13:12:59 -0700.
654
655 class ESONTT(Observatory):
656     """
657     European Southern Observatory, NTT, La Silla
658     """
659     def __init__(self):
660         self.name = "European Southern Observatory, NTT, La Silla."
661         self.longitude = 70.7317422222 * u.degree # West
662         self.latitude = -28.7448777778 * u.degree # North
663         self.altitude = 2375 * u.meter
664         self.timezone = 4 * u.hourangle
665
666 class ES036M(Observatory):
667     """
668     European Southern Observatory, 3.6m Telescope, La Silla
669     """
670     def __init__(self):
671         self.name = "European Southern Observatory, 3.6m Telescope, La Silla."
672         self.longitude = 70.7296127778 * u.degree # West
673         self.latitude = -28.7428294444 * u.degree # North
674         self.altitude = 2400 * u.meter
675         self.timezone = 4 * u.hourangle
676
677 class ES0VLT(Observatory):
678     """
679     European Southern Observatory, VLT, Paranal
680     """
681     def __init__(self):
682         self.name = "European Southern Observatory, VLT, Paranal."
683         self.longitude = 70.4022 * u.degree # West
684         self.latitude = -24.6253 * u.degree # North
685         self.altitude = 2648 * u.meter
686         self.timezone = 4 * u.hourangle
687
688 # Submitted by Giovanni Catanzaro, 7/17/03.
689 class SLN(Observatory):
690     """
691     SLN - Catania Astrophysical Observatory
692     """
693     def __init__(self):
694         self.name = "SLN - Catania Astrophysical Observatory."
695         self.longitude = 345.026666667 * u.degree # West
696         self.latitude = 37.6916666667 * u.degree # North
697         self.altitude = 1725. * u.meter
698         self.timezone = -1 * u.hourangle
699
700 # Submitted by Ahmet Devlen, 4/21/04
701 class EUO(Observatory):
702     """
703     Ege University Observatory
704     """
705     def __init__(self):
706         self.name = "Ege University Observatory"
707         self.longitude = -26.725 * u.degree # West
708         self.latitude = 38.3983333333 * u.degree # North
709         self.altitude = 795. * u.meter
710         self.timezone = 2 * u.hourangle
711
712 # Submitted by Zeki Aslan 8/15/05 who said the "tno" entry was wrong.
713 class TNO(Observatory):
714     """
715     Turkiye National Observatory
716     """
717     def __init__(self):
718         self.name = "Turkiye National Observatory"
719         self.longitude = -29.6469444444 * u.degree # West
720         self.latitude = 36.8244444444 * u.degree # North
721         self.altitude = 2555. * u.meter
722         self.timezone = 2 * u.hourangle
723
724 class TUG(Observatory):
725     """
726     TUBITAK National Observatory, Turkey
727     """
728     def __init__(self):
729         self.name = "TUBITAK National Observatory, Turkey."
730         self.longitude = -29.6666666667 * u.degree # West

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733     self.latitude = 36.825 * u.degree # North
734     self.altitude = 2547. * u.meter
735     self.timezone = -2 * u.hourangle
736
737
738 # Submitted by Ricky Patterson for Vatican Obs. Research Group, 6/15/04
739 class MGO(Observatory):
740     """
741     Mount Graham Observatory
742     """
743     def __init__(self):
744         self.name = "Mount Graham Observatory"
745         self.longitude = 109.891666667 * u.degree # West
746         self.latitude = 32.7016666667 * u.degree # North
747         self.altitude = 3181 * u.meter
748         self.timezone = 7 * u.hourangle
749
750 # Submitted by Jeewan C. Bandey 7/28/05
751 # Changed to W longitude MJF 4/1/06)
752 # (E) longitude = 79.45639
753 class ARIES(Observatory):
754     """
755     Aryabhata Research Institute of Observational Sciences
756     """
757     def __init__(self):
758         self.name = "Aryabhata Research Institute of Observational Sciences."
759         self.longitude = 280.54361 * u.degree # West
760         self.latitude = 29.36 * u.degree # North
761         self.altitude = 1950. * u.meter
762         self.timezone = -5.5 * u.hourangle
763
764 # Submitted by Eduardo Fern?ndez Laj?s 10/28/05
765 class OALP(Observatory):
766     """
767     Observatorio Astronomico de La Plata
768     """
769     def __init__(self):
770         self.name = "Observatorio Astronomico de La Plata"
771         self.longitude = 57.9322995 * u.degree # West
772         self.latitude = -33.0932488889 * u.degree # North
773         self.altitude = 20. * u.meter
774         self.timezone = 3. * u.hourangle
775
776 # Submitted by Leslie F. Brown 7/29/06
777 class OLIN(Observatory):
778     """
779     Connecticut College - Olin Observatory
780     """
781     def __init__(self):
782         self.name = "Connecticut College - Olin Observatory"
783         self.longitude = 72.1052777778 * u.degree # West
784         self.latitude = 41.3788888889 * u.degree # North
785         self.altitude = 85 * u.meter
786         self.timezone = 5 * u.hourangle
787
788 # Submitted by Pat van Heerden 11/20/06
789 class BOYDEN(Observatory):
790     """
791     Boyden Observatory
792     """
793     def __init__(self):
794         self.name = "Boyden Observatory"
795         self.longitude = 332.594444444 * u.degree # West
796         self.latitude = -28.9611111111 * u.degree # North
797         self.altitude = 1387 * u.meter
798         self.timezone = -2 * u.hourangle
799
800 # Submitted by Mike Yang 8/19/09
801 class LULIN(Observatory):
802     """
803     Lulin Observatory
804     """
805     def __init__(self):
806         self.name = "Lulin Observatory"
807         self.longitude = 240.873333333 * u.degree # West
808         self.latitude = 23.468333333 * u.degree # North
809         self.altitude = 2862. * u.meter
810         self.timezone = -8 * u.hourangle
811
812 # Submitted by Mairan Teodoro 1/27/10
813 class SOAR(Observatory):
814     """
815     Southern Astrophysical Research Telescope
816     """
817     def __init__(self):
818         self.name = "Southern Astrophysical Research Telescope."
819         self.longitude = 70.733722222 * u.degree # West
820         self.latitude = -29.762 * u.degree # North
821         self.altitude = 2738 * u.meter
822         self.timezone = 4 * u.hourangle
823
824 # Submitted from iraf.net 4/12/10

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825 class BAKER(Observatory):
826     """
827     Baker Observatory
828     """
829     def __init__(self):
830         self.name = "Baker Observatory"
831         self.longitude = 93.0417472222 * u.degree # West
832         self.latitude = 37.398625 * u.degree # North
833         self.altitude = 418.2 * u.meter
834         self.timezone = 6 * u.hourangle
835
836 # Added MJF 6/1/2010
837 class HET(Observatory):
838     """
839     McDonald Observatory - Hobby-Eberly Telescope
840     """
841     def __init__(self):
842         self.name = "McDonald Observatory - Hobby-Eberly Telescope."
843         self.longitude = 104.014722222 * u.degree # West
844         self.latitude = 30.68144444 * u.degree # North
845         self.altitude = 2026 * u.meter
846         self.timezone = 6 * u.hourangle
847
848 # Submitted by Robert D. Collier 9/1/10
849 class JCDO(Observatory):
850     """
851     Jack C. Davis Observatory, Western Nevada College
852     """
853     def __init__(self):
854         self.name = "Jack C. Davis Observatory, Western Nevada College"
855         self.longitude = 119.790666667 * u.degree # West
856         self.latitude = 39.1857222222 * u.degree # North
857         self.altitude = 1534 * u.meter
858         self.timezone = 8 * u.hourangle
859
860 # Submitted by mas_nomi1711@yahoo.com 3/16/12
861 class LNO(Observatory):
862     """
863     Langkawi National Observatory
864     """
865     def __init__(self):
866         self.name = "Langkawi National Observatory"
867         self.longitude = 260.218888889 * u.degree # West
868         self.latitude = 6.30694444444 * u.degree # North
869         self.altitude = 111 * u.meter
870         self.timezone = -8 * u.hourangle

```

C.15 .. SLiPy . Plot

```
1  # Copyright (c) Geoffrey Lentner 2015. All Rights Reserved.
2  # See LICENSE (GPLv3)
3  # AstroPython/Astro/Plot.py
4  """
5  Plotting facility for astronomy.
6  """
7  import matplotlib as mpl
8  from matplotlib import pyplot as plt
9
10 from .. import SlipyError
11 from ..Framework.Options import Options, OptionsError
12 from . import Fits, Spectrum
13
14 mpl.rcParams['figure.facecolor'] = 'w'
15 plt.ion()
16
17 class PlotError(SlipyError):
18     """
19     Exception specific to Plot module.
20     """
21     pass
22
23 class SPlot:
24     """
25     SPlot( spectrum, **kwargs )
26
27     Spectrum Plot - Plot the data in 'spectrum'.
28     """
29     def __init__(self, spectrum, **kwargs):
30         """
31         Assign 'options' in 'kwargs' and initialize the figure.
32         """
33         try:
34             # available options
35             self.options = Options( kwargs,
36                 {
37                     'marker': 'b-' , # marker for plot
38                     'label' : 'unspecified' , # label for data
39                     'usetex': False      # pdflatex setting
40                 })
41
42             # assign options
43             self.usetex = self.options('usetex')
44             self.ylimits = []
45             self.gridv = None
46             self.yargs = []
47             self.xargs = []
48             self.largs = []
49             self.targs = []
50             self.xkwargs = {}
51             self.ykwargs = {}
52             self.tkwargs = {}
53             self.lkwargs = {}
54             self.txargs = []
55             self.txkwargs = []
56
57             if type(spectrum) is not Spectrum.Spectrum:
58                 raise PlotError('Splot expects type 'Spectrum!')
59
60             # data in 'list' allows for overplotting
61             self.data = [ spectrum.data ]
62             self.wave = [ spectrum.wave ]
63
64             if spectrum.data.unit:
65                 self.yargs = [str(spectrum.data.unit)]
66
67             if spectrum.wave.unit:
68                 self.xargs = [str(spectrum.wave.unit)]
69
70             # 'name' always retains 'label'
71             self.name = self.options('label')
72
73             # 'label' and 'marker's same as data
74             self.label = [ self.options('label') ]
75             self.marker = [ self.options('marker') ]
76
77             # set x limits to the data
78             self.xlimits = [ spectrum.wave.min().value,
79                             spectrum.wave.max().value ]
80
81         except OptionsError as err:
82             print( "--> OptionsError:", err.msg)
83             raise PlotError("Failed to construct SPlot.")
84
85         # initialize the figure
86         self.fig = plt.figure("Spectral-Plot (SLiPy)")
87         self.ax = self.fig.add_subplot(111)
88         self.draw()
89
```

```

90     def xlim(self, xmin, xmax ):
91         """
92         Handle to pyplot.xlim
93         """
94         self.xlimits = [ xmin, xmax ]
95         self.ax.set_xlim(xmin, xmax)
96
97     def ylim(self, ymin, ymax ):
98         """
99         Handle to pyplot.ylim
100        """
101        self.ylimits = [ ymin, ymax ]
102        self.ax.set_ylim(ymin, ymax)
103
104    def xlabel(self, *args, **kwargs ):
105        """
106        x axis label.
107        """
108        self.xargs = args
109        self.xkwargs = kwargs
110        self.ax.set_xlabel( *args, **kwargs )
111
112    def ylabel(self, *args, **kwargs ):
113        """
114        y axis label.
115        """
116        self.yargs = args
117        self.ykwargs = kwargs
118        self.ax.set_ylabel( *args, **kwargs )
119
120    def title(self, *args, **kwargs ):
121        """
122        title for plot.
123        """
124        self.targs = args
125        self.tkwargs = kwargs
126        self.ax.set_title( *args, **kwargs )
127
128    def legend(self, *args, **kwargs):
129        """
130        legend for plot.
131        """
132        self.largs = args
133        self.lkwargs = kwargs
134        plt.legend( *args, **kwargs )
135
136    def text(self, *args, **kwargs):
137        """
138        display text over plot.
139        """
140        self.txargs.append( args )
141        self.txkwargs.append( kwargs )
142        self.ax.text( *args, **kwargs )
143
144    def txtclear(self):
145        """
146        Clear all 'text' from figure.
147        """
148        self.txargs = []
149        self.txkwargs = []
150        self.draw()
151
152    def markers(self, *args):
153        """
154        Reassign the values for the 'marker's in the figure. The number
155        of arguments must equal the number of spectra in the figure. This
156        starts out as one, but will increase for ever SPlot.overlay().
157        """
158        if len(args) != len(self.data):
159            raise PlotError('{} arguments were given but there are {} '
160                            'spectra plotted in this figure!'.format(len(args), len(self.data)))
161
162        for a, mark in enumerate(args):
163            if type(mark) is not str:
164                raise PlotError('Arguments given to SPlot.markers() must be '
165                                '{} but argument #{} was {}'.format(type(''), a+1, type(mark)))
166
167        self.marker = list(args)
168
169    def __build(self, picker = False):
170        """
171        Make the plot.
172        """
173
174        if picker:
175            self.restore()
176            self.ax.plot(self.wave[0], self.data[0], self.marker[0],
177                        label = self.label[0], picker = True)
178
179        else:
180            for x, y, m, l in zip(self.wave, self.data, self.marker, self.label):
181                self.ax.plot(x, y, m, label=l)

```

```

182
183     if self.xargs or self.xkwargs:
184         self.xlabel( *self.xargs, **self.xkwargs )
185
186     if self.yargs or self.ykwargs:
187         self.ylabel( *self.yargs, **self.ykwargs )
188
189     if self.targs or self.tkwargs:
190         self.title( *self.targs, **self.tkwargs )
191
192     if self.largs or self.lkwargs:
193         self.legend( *self.largs, **self.lkwargs )
194
195     if self.txargs or self.txkwargs:
196         for args, kwargs in zip(self.txargs, self.txkwargs):
197             self.ax.text( *args, **kwargs )
198
199     if self.xlimits:
200         self.xlim( *self.xlimits )
201
202     if self.ylimits:
203         self.ylim( *self.ylimits )
204
205     if self.gridv:
206         self.grid(self.gridv)
207
208     if self.usetex:
209         plt.rc('text', usetex=True)
210         plt.rc('font', family='serif')
211
212     def refresh(self):
213         """
214         pyplot.draw()
215         """
216         plt.draw()
217
218     def draw(self, picker = False):
219         """
220         Re-build the plot
221         """
222         self.ax.clear()
223         self._build(picker = picker)
224         plt.draw()
225
226     def close(self):
227         """
228         Close the plot.
229         """
230         plt.close("Spectral-Plot (SLiPy)")
231
232     def grid(self, value):
233         """
234         Show grid on plot.
235         """
236         self.gridv = value
237         plt.grid(value)
238
239     def save(self, filename):
240         """
241         Save plot to 'filename'. Must have extension for formatting.
242         """
243         if type(filename) is not str:
244             raise PlotError('filename should be of type str.')
245         if len(filename.split('.')) < 2:
246             raise PlotError('filename needs an extension.')
247
248         plt.savefig(filename, format=filename.split('.')[1])
249
250     def xoffset(self, value):
251         """
252         Toggle the offset for the x axis
253         """
254         plt.gca().get_xaxis().get_major_formatter().set_useOffset(value)
255
256     def yoffset(self, value):
257         """
258         Toggle the offset for the y axis
259         """
260         plt.gca().get_yaxis().get_major_formatter().set_useOffset(value)
261
262     def tight_layout(self):
263         """
264         pyplot.tight_layout()
265         """
266         plt.tight_layout()
267
268     def overlay(self, *splots ):
269         """
270         Overlay (add) spectra to this plot from other 'splots'.
271         """
272
273         for a, plot in enumerate(splots):

```

```

274
275         # check data type
276         if type(plot) is not SPlot:
277             raise PlotError('Splot.overlay expects '
278                             'type Splot! (from argument {})'
279                             .format(a))
280
281         # add data
282         self.data += plot.data
283         self.wave += plot.wave
284         self.marker += plot.marker
285         self.label += plot.label
286
287     def restore(self):
288         """
289         Restore self.data and self.wave from possible 'overlay's.
290         """
291         self.data = [ self.data[0] ]
292         self.wave = [ self.wave[0] ]
293         self.marker = [ self.marker[0] ]
294         self.label = [ self.label[0] ]
295
296     def desired( plot ):
297         """
298         Helper function for Iterate. Prompts user to keep 'plot';
299         returns True or False.
300         """
301         # draw the plot
302         plot.draw()
303         # prompt the user for input
304         prompt = input('\r\033[K keep -> '{}' (y/[n]/x)? : '
305                       .format(plot.name)).strip()
306         # insure valid response
307         while True:
308             if prompt not in ['y','n','','x']:
309                 # invalid input, prompt again
310                 print('\r\033[K '{}' was not a recognized response.'
311                       .format(prompt))
312                 prompt = input('\033[2A\r\033[K keep -> '{}' (y/[n]/x)? : '
313                               .format(plot.name)).strip()
314             else:
315                 # clear the error message
316                 print('\r\033[K\033[1A')
317                 break
318
319         if prompt in ['n', '']:
320             return False
321         elif prompt in ['y']:
322             return True
323         else:
324             # the user input 'x'
325             raise KeyboardInterrupt('\r\033[K User exited early, saving results.')
326
327     def Iterate( *plots, **kwargs ):
328         """
329         Iterate( *plots, **kwargs ):
330
331         Iterate thru 'plots' to inspect data, the user marks 'plots' of
332         interest. The function returns a list of 'names' marked.
333         """
334         try:
335             options = Options( kwargs,
336                               {
337                                   'keep' : 'name' # alternatively, 'plot'
338                               })
339
340             keep = options('keep')
341
342             if keep not in ['name', 'plot']:
343                 raise PlotError('Iterate expects either 'name' or 'plot' for '
344                                 'keyword argument 'keep'.')
345
346             # check input arguments
347             for plot in plots:
348                 if not hasattr(plot, 'draw'):
349                     raise PlotError('Iterate expects objects to '
350                                     'have a 'draw' method.')
351                 if not hasattr(plot, 'name'):
352                     raise PlotError('Iterate expects objects to '
353                                     'have a 'name' method.')
354
355             # clear some space
356             print('\n')
357
358             keepers = []
359             for a, plot in enumerate(plots):
360                 print('\033[2A\r\033[K Showing plot {} of {} ... '
361                       .format(a, len(plots)) )
362                 if desired( plot ):
363                     if keep == 'name':
364                         keepers.append( plot.name )
365

```

```
366         elif keep == 'plot':
367             keepers.append( plot )
368
369         return keepers
370
371     except OptionsError as err:
372         print(' --> OptionsError:', err.msg)
373         raise PlotError('Failed to initialize Iterate.')
374
375     except KeyboardInterrupt as x:
376         print(x)
377         return keepers
```

C.16 .. SLiPy . Profile

```
1  # Copyright (c) Geoffrey Lentner 2015. All Rights Reserved.
2  # See LICENSE (GPLv3)
3  # slipy/SLiPy/Profile.py
4
5  """
6  Profile fitting tasks for spectra.
7  """
8  import numpy as np
9  from scipy.optimize import curve_fit
10 from scipy.interpolate.interpolate import interp1d
11 from scipy.special import wofz as w
12 from scipy.integrate import.simps as Integrate
13
14 from matplotlib import pyplot as plt
15 from matplotlib.lines import Line2D
16 from matplotlib import widgets
17
18 from astropy import units as u
19 from astropy.constants import m_e, e, c
20
21 from .. import SlipyError
22
23 from .Observatory import Observatory
24 from .Spectrum import Spectrum, SpectrumError
25 from .Plot import SPlot, PlotError
26
27 from ..Framework.Options import Options, OptionsError
28 from ..Framework.Measurement import Measurement
29 from ..Algorithms.Functions import Gaussian, Lorentzian, Voigt, InvertedLorentzian
30 from ..Algorithms.KernelFit import KernelFit1D
31 from ..Data import Atomic
32
33 class ProfileError(SlipyError):
34     """
35     Exception specific to Profile module.
36     """
37     pass
38
39 def Pick(event):
40     """
41     Used to hand selection events.
42     """
43     if isinstance(event.artist, Line2D):
44         # get the x, y data from the pick event
45         thisline = event.artist
46         xdata = thisline.get_xdata()
47         ydata = thisline.get_ydata()
48         ind = event.ind
49         # update the selection dictionary
50         global selected
51         selected['wave'].append(np.take(xdata, ind)[0])
52         selected['data'].append(np.take(ydata, ind)[0])
53         # display points as a visual aid
54         plt.scatter(np.take(xdata, ind)[0], np.take(ydata, ind)[0],
55                   marker = 'o', s=75, edgecolor='red', facecolor='None', lw=2)
56         plt.draw()
57
58 # empty selection dictionary is filled with the Select() function
59 selected = {'wave': [], 'data': []}
60
61 def Select(splot):
62     """
63     Select points from the 'splot'. This should be of type SPlot
64     (or it can optionally be a Spectrum type, for which a SPlot will be
65     created). The splot will be rendered and the user clicks on the
66     figure. When finished, return to the terminal prompt. A dictionary is
67     returned with two entries, 'wave' and 'data', representing the x-y
68     locations selected by the user. This can always be retrieved later by
69     accessing the module member 'Profile.selected'.
70     """
71     if type(splot) is Spectrum:
72         splot = SPlot(splot)
73
74     elif type(splot) is not SPlot:
75         raise ProfileError('Select() requires either a Spectrum or SPlot '
76                             'object as an argument')
77
78     # reset the selection dictionary
79     global selected
80     selected = {'wave': [], 'data': []}
81
82     splot.draw(picker = True)
83
84     splot.fig.canvas.mpl_connect('pick_event', Pick)
85
86     input(' Press <Return> after making your selections ... ')
87     return selected
88
89 def AutoFit(splot, function = InvertedLorentzian, params = None):
```



```

90     """
91     Given 'splot' of type SPlot, the user selects four points on the
92     spectrum and a parameterized function is fit (an inverted Lorentzian by
93     default). Optionally, 'splot' can be of type spectrum and a basic SPlot
94     will be created for you. If the user gives an alternative 'function',
95     'params' (parameters) must be provided. 'params' is to be the first guess,
96     'p0' given to scipy...curve_fit; the user can provide them explicitly,
97     or in the form of functions with the template 'function(xarray, yarray)'
98     where 'xarray' and 'yarray' are the 'wave' and 'data' arrays extracted
99     between the two points selected by the user.
100    """
101
102    print(' Please select four points identifying the spectral line.')
103    print(' Outer points mark the domain of the line.')
104    print(' Inner points mark the sample of the line to fit.')
105
106    # make selections
107    selected = Select(splot)
108
109    if len( selected['wave'] ) != 4:
110        raise ProfileError('Exactly 4 locations should be selected for '
111            'the Profile.AutoFit() routine!')
112
113    # order the selected wavelength locations
114    points = selected['wave']
115    points.sort()
116
117    # get data and wavelength arrays
118    if type(splot) is SPlot:
119        wave, data = splot.wave[0], splot.data[0]
120    else:
121        wave, data = splot.wave, splot.data
122
123    # extract the domains 'selected' (i.e., the sample interval)
124    x_inner = wave[np.where(np.logical_and(points[1] < wave, wave < points[2]))]
125    x_outer = wave[np.where(np.logical_and(points[0] < wave, wave < points[3]))]
126    y_inner = data[np.where(np.logical_and(points[1] < wave, wave < points[2]))]
127    y_outer = data[np.where(np.logical_and(points[0] < wave, wave < points[3]))]
128
129    if function.__name__ == 'InvertedLorentzian':
130        # First guess for default behavior
131        params = [ y_inner.min().value, x_inner[ y_inner.argmax() ].value,
132            (x_inner[-1] - x_inner[0]).value / 2]
133
134    elif not params:
135        # the user gave a different function but not parameters!
136        raise ProfileError('The user must provide 'params' when giving an '
137            'alternative 'function' in Profile.Fit()!')
138
139    else:
140
141        if not hasattr(params, '__iter__'):
142            raise ProfileError('params' must be an iterable type in '
143                'Profile.AutoFit()!')
144
145        try:
146            for a, parameter in enumerate(params):
147                if type(parameter) is type(InvertedLorentzian):
148                    # replace parameter with function evaluation
149                    params[a] = parameter(x_inner, y_inner)
150
151        except TypeError as err:
152            print(' --> TypeError:', err)
153            raise ProfileError('Profile.AutoFit() failed to call user functions '
154                'correctly in 'params'!')
155
156    # fit a parameterized curve
157    coeff, var_matrix = curve_fit(
158        function, # function to call, default is InvertedLorentzian
159        x_inner.value, # domain (without units)
160        y_inner.value, # data (without units)
161        p0 = params # list of parameters to try as a first guess
162    )
163
164    # display visual aids ...
165    # evaluation of the fit profile over larger domain
166    plt.plot(x_outer, function(x_outer.value, *coeff) * y_outer.unit,
167        'b--', linewidth = 4)
168    plt.plot(x_inner, function(x_inner.value, *coeff) * y_inner.unit,
169        'r-', linewidth = 4)
170
171    # return the larger domain, evaluated and of type Spectrum
172    return Spectrum(function(x_outer.value, *coeff) * y_outer.unit, x_outer)
173
174
175    def Extract(splot, kernel = Gaussian, **kwargs):
176        """
177        Select locations in the 'splot' figure, expected to be of type SPlot.
178        Exactly four points should be selected. These are used to extract a
179        line profile from the spectrum plotted in the splot figure. The inner
180        section is used for the line, and the outer selection is used to model
181        the continuum; these, respectively, and both returned as Spectrum objects.

```

```

182 The gap is jumped using 1D interpolation (scipy...interp1d).
183 """
184 try:
185
186     options = Options( kwargs, {
187         'kind'      : 'cubic', # given to scipy...interp1d for continuum
188         'bandwidth' : 0.1*u.nm # user should provide this!
189         # 'rms'      : False    # measure the RMS of the line, continuum
190     })
191
192     kind      = options('kind')
193     bandwidth = options('bandwidth')
194     # rms      = options('rms')
195
196 except OptionsError as err:
197     print(' --> OptionsError:', err)
198     raise ProfileError('Unrecognized option given to Extract(!)')
199
200 print(' Please select four points identifying the spectral line.')
201 print(' Outer intervals sample the continuum.')
202 print(' Center interval contains the line.')
203
204 # make selections
205 selected = Select(splot)
206
207 if len( selected['wave'] ) != 4:
208     raise ProfileError('Exactly 4 locations should be selected for '
209         'the profile modeling to work!')
210
211 # order the selected wavelength locations
212 wave = selected['wave']
213 wave.sort()
214
215 # create 'line' profile
216 x1 = splot.wave[0].copy()
217 y1 = splot.data[0].copy()
218 y1 = y1[ x1[ x1 < wave[2] ] > wave[1] ]
219 x1 = x1[ x1[ x1 < wave[2] ] > wave[1] ]
220 line = Spectrum(y1, x1)
221
222 # extract continuum arrays
223 xc = splot.wave[0].copy()
224 yc = splot.data[0].copy()
225 # inside outer-most selections
226 yc = yc[ xc[ xc < wave[3] ] > wave[0] ]
227 xc = xc[ xc[ xc < wave[3] ] > wave[0] ]
228 # keep wavelengths whole domain for later
229 xx = xc.copy()
230 yy = yc.copy()
231 # but not the line
232 yc = yc[np.where(np.logical_or(xc < wave[1], xc > wave[2]))]
233 xc = xc[np.where(np.logical_or(xc < wave[1], xc > wave[2]))]
234
235 # use 'kernel smoothing' to model the continuum
236 model = KernelFit1D(xc, yc, kernel = kernel, bandwidth = bandwidth)
237
238 # interpolate to cross 'the gap'
239 interp = interp1d(xc, model.mean(xc), kind = kind)
240
241 # continuum model outside the line
242 cont_outside = interp(xc)
243
244 # continuum inside the line
245 cont_inside = interp(x1)
246
247 # continuum model for whole domain
248 cont_domain = interp(xx)
249
250 # build a spectrum from the arrays
251 continuum = Spectrum(cont_domain, xx)
252
253 # display visual aid
254 plt.plot(xx, cont_domain, 'r--', linewidth = 3)
255 plt.fill_between(x1, y1, cont_inside, color = 'blue', alpha = 0.25)
256 plt.draw()
257
258 # if not rms:
259 #     return line, continuum
260
261 continuum.rms = np.sqrt( np.sum( (cont_outside * yc.unit - yc)**2 ) / len(yc) )
262 continuum.rms *= continuum.data.unit
263
264 return line, continuum
265
266
267 def OpticalDepth(line, continuum, error=None, boost=None):
268     """
269     Given an absorption 'line' and its background 'continuum', compute the
270     apparent optical depth Spectrum. Both the line and the continuum must
271     be of Spectrum type. The continuum will be resampled to the pixel space of the
272     line if it is not currently.
273
274     If provided an 'error' spectrum, it should either have the same units as the 'line'

```

```

275 or be in percent units (they should have identical wavelength arrays). An upper and
276 lower uncertainty will be computed by adding and subtracting before the calculation.
277 Further, if an 'rms' value is attached to the 'continuum' giving the percent error in
278 the continuum fit, this will be added in quadrature to the error spectrum before hand.
279
280 'boost' allows for artificially increasing the resolution by resampling to more pixels.
281 If the spectrum is not of sufficiently high resolution, the integration could suffer
282 numerical errors. If provided, this should be a percentage to increase the resolution
283 (e.g., 'boost=2' would double the resolution by interpolating in between the pixels).
284
285 This function returns a Spectrum with 'upper' and 'lower' bounds attached.
286 """
287 if not isinstance(line, Spectrum):
288     raise ProfileError('OpticalDepth() expects the first argument to be of '
289                        "'Spectrum' type!")
290
291 if not isinstance(continuum, Spectrum):
292     raise ProfileError('OpticalDepth() expects the second argument to be of '
293                        "'Spectrum' type!")
294
295 line = line.copy()
296 continuum = continuum.copy()
297
298 if error:
299     if not isinstance(error, Spectrum):
300         raise ProfileError('OpticalDepth() expects the 'error' to be of 'Spectrum' type!')
301     if error.data.unit not in [line.data.unit, u.percent]:
302         raise ProfileError('OpticalDepth() expects the 'error' spectrum to have either '
303                            'the same units as the 'line' or units of 'percent'.')
304
305     error = error.copy()
306
307     if error.data.unit == u.percent:
308         if np.logical_and(error.data.value < 0, error.data.value > 100).any():
309             raise ProfileError('OpticalDepth() was given an 'error' spectrum in '
310                                'units of 'percent' with values outside of 0 and 100!')
311
312     error.resample(line)
313     error.data = (error.data * line.data).to(line.data.unit)
314
315 if hasattr(continuum, 'rms'):
316     if not hasattr(continuum.rms, 'unit') or (continuum.rms.unit not in
317        [continuum.data.unit, u.percent]):
318         raise ProfileError('OpticalDepth() expects a 'continuum' with an 'rms' '
319                            'attribute to have the same units or 'percent' units.')
320
321     rms = continuum.rms
322     if rms.unit == u.percent:
323         rms = rms * continuum.data
324         rms = rms.to(continuum.data.unit)
325
326     if not error:
327         error = rms
328
329     else:
330         # add the two error components in quadrature
331         error.resample(line)
332         error = Spectrum(np.sqrt(rms**2 + error.data**2) * line.data.unit, line.wave)
333
334 # boost the resolution of the spectrum if requested
335 if boost: line.resample( line.wave[0], line.wave[-1], len(line) * boost )
336
337 # resample the continuum spectrum, nothing happens if they are already the same
338 continuum.resample(line)
339
340 # compute the apparent optical depth
341 tau = Spectrum(np.log((continuum / line).data.decompose()), line.wave)
342
343 if error:
344     tau.lower = Spectrum(np.log((continuum / (line - error)).data.decompose()), line.wave)
345     tau.upper = Spectrum(np.log((continuum / (line + error)).data.decompose()), line.wave)
346
347 return tau
348
349 def EquivalentWidth(line, continuum, error=None, boost=None):
350     """
351     Given an absorption 'line' and its background 'continuum', compute the
352     equivalent width, 'W', of the feature. Both the line and the continuum must
353     be of Spectrum type. The continuum will be resampled to the pixel space of the
354     line if it is not currently.
355
356     If provided an 'error' spectrum, it should either have the same units as the 'line'
357     or be in percent units (they should have identical wavelength arrays). An upper and
358     lower uncertainty will be computed by adding and subtracting before the calculation.
359     Further, if an 'rms' value is attached to the 'continuum' giving the percent error in
360     the continuum fit, this will be added in quadrature to the error spectrum before hand.
361
362     'boost' allows for artificially increasing the resolution by resampling to more pixels.
363     If the spectrum is not of sufficiently high resolution, the integration could suffer
364     numerical errors. If provided, this should be a percentage to increase the resolution
365     (e.g., 'boost=2' would double the resolution by interpolating in between the pixels).
366

```

```

367 Integration is performed using the composite Simpson's rule (scipy.integrate.simps)
368 This function returns a 'Measurement' object (..Framework.Measurement.Measurement).
369 """
370 tau = OpticalDepth(line, continuum, error=error, boost=boost)
371 W = Integrate(1 - np.exp(-tau.data.decompose()), tau.wave) * line.wave.unit
372
373 if error:
374     upper = Integrate(1 - np.exp(-tau.lower.data.decompose()), tau.wave) * line.wave.unit
375     lower = Integrate(1 - np.exp(-tau.upper.data.decompose()), tau.wave) * line.wave.unit
376
377     # join upper/lower into +/- set
378     uncertainty = np.array([(upper - W).value, (lower - W).value]) * tau.wave.unit
379
380 else: uncertainty = None
381
382 return Measurement(W, error = uncertainty, name = 'Equivalent Width',
383                   notes = 'Measured using Profile.EquivalentWidth() from SLiPy')
384
385
386 def ColumnDensity(line, continuum, ion, error=None, boost=None, weakline=None, integrate=True):
387     """
388     Given an absorption 'line' and its background 'continuum', compute the
389     apparent column density, 'N', of the feature. Both the line and the continuum must
390     be of Spectrum type. The continuum will be resampled to the pixel space of the
391     line if it is not currently. An 'ion' must be provided (type Atomic.Ion) with
392     members, 'fvalue' (oscillator strength) and 'wavelength' (will be converted to
393     Angstroms).
394
395     If provided an 'error' spectrum, it should either have the same units as the 'line'
396     or be in percent units (they should have identical wavelength arrays). An upper and
397     lower uncertainty will be computed by adding and subtracting before the calculation.
398     Further, if an 'rms' value is attached to the 'continuum' giving the percent error in
399     the continuum fit, this will be added in quadrature to the error spectrum before hand.
400
401     With 'integrate' set to True (the default) the integrated apparent column density will
402     be returned (as type Measurement and in units of cm-2). Otherwise, a Spectrum is
403     returned as a function of wavelength and the '.upper' and '.lower' bounds are attached.
404
405     'boost' allows for artificially increasing the resolution by resampling to more pixels.
406     If the spectrum is not of sufficiently high resolution, the integration could suffer
407     numerical errors. If provided, this should be a percentage to increase the resolution
408     (e.g., 'boost=2' would double the resolution by interpolating in between the pixels).
409
410     With a 'weakline' provided (the results of this function on the weaker absorption
411     line for a doublet) a correction gives an approximate 'true' column density (attached
412     to the returned Measurement as '.true'), see Savage & Sembach, 1991.
413
414     Integration is performed using the composite Simpson's rule (scipy.integrate.simps)
415     This function returns a 'Measurement' object (..Framework.Measurement.Measurement).
416     """
417     if (not isinstance(ion, Atomic.Ion) or not hasattr(ion, 'fvalue') or
418         not hasattr(ion, 'wavelength')): raise ProfileError("From ColumnDensity(), 'ion' is "
419         "expected to be of type Atomic.Ion and have members 'fvalue' and 'wavelength'!")
420
421     if weakline and not hasattr(weakline, 'unit'):
422         raise ProfileError("From ColumnDensity(), 'weakline' is expected to have units!")
423
424     const = (1.13e12 / u.cm) / (ion.fvalue * ion.wavelength.to(u.cm))
425     tau = OpticalDepth(line, continuum, error=error, boost=boost)
426     N = tau * const / ion.wavelength.to(u.AA).value
427     N.upper = tau.upper * const / ion.wavelength.to(u.AA).value
428     N.lower = tau.lower * const / ion.wavelength.to(u.AA).value
429
430     if not integrate and not weakline:
431         return N
432
433     elif weakline and not integrate:
434         raise ProfileError("From ColumnDensity(), you gave 'integrate' as False but we "
435         "need to integrate to solve for the correct N using the 'weakline'!")
436
437     upper = Integrate(N.upper.data, N.wave) / u.cm**2
438     lower = Integrate(N.lower.data, N.wave) / u.cm**2
439     N = Integrate(N.data, N.wave) / u.cm**2
440     uncertainty = np.array([(N - upper).value, (lower - N).value]) / u.cm**2
441
442     N = Measurement(N, name="Column Density (Apparent)",
443                   error=uncertainty, notes="Measured using Profile.ColumnDensity() from SLiPy")
444
445     if not weakline:
446         return N
447
448     # attach the 'correction' given the already computed 'weakline' column density.
449     diff = np.log10(weakline.to(1 / u.cm**2).value) - np.log10(N.value)
450     if diff < 0.0 or diff > 0.24:
451         raise ProfileError("From ColumnDensity(), the difference between the doublet "
452         "lines is too great to solve for a correction using published results!")
453
454     # Table 4: Column Density Corrections for an Isolated Gaussian Component
455     # Savage & Sembach (1991)
456     table = np.array([ [0.000, 0.000], [0.010, 0.010], [0.020, 0.020], [0.030, 0.030],
457                       [0.040, 0.040], [0.050, 0.051], [0.060, 0.061], [0.070, 0.073], [0.080, 0.085],
458                       [0.090, 0.097], [0.100, 0.111], [0.110, 0.125], [0.120, 0.140], [0.130, 0.157],

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```

460     [0.140, 0.175], [0.150, 0.195], [0.160, 0.217], [0.170, 0.243], [0.180, 0.273],
461     [0.190, 0.307], [0.200, 0.348], [0.210, 0.396], [0.220, 0.453], [0.230, 0.520],
462     [0.240, 0.600]]
463
464     N.correction = interp1d(table[:,0], table[:,1], kind='cubic')(diff)
465     N.true       = 10**(np.log10(weakline.to(1/u.cm**2).value) + N.correction) / u.cm**2
466     return N
467
468
469 class FittingGUI:
470     """
471     Graphical Interface (keeps references alive) for fitting analytical
472     profiles to spectral data.
473     """
474     def __init__(self, splot, obs=None, ion=None, function='Voigt', **kwargs):
475         """
476         Build widget elements based on a spectrum plotted in 'splot' (type SPlot).
477         'splot' may also be a Spectrum object (for which a SPlot will be created).
478
479         Make initial guesses at parameters, build widgets, render the figure.
480         """
481         try:
482             options = Options( kwargs, {
483
484                 'kind'      : 'cubic', # given to interp1d for continuum
485                 'bandwidth' : 0.1*u.nm, # user should provide this!
486             })
487
488             kind      = options('kind')
489             bandwidth = options('bandwidth')
490
491         except OptionsError as err:
492             print(' --> OptionsError:', err)
493             raise ProfileError('Unrecognized option given to FittingGUI.__init__()')
494
495         if function not in ['Voigt', 'Lorentzian', 'Gaussian']:
496             raise ProfileError('The only currently implemented functions '
497                                'for fitting profiles are 'Voigt', 'Lorentzian' and 'Gaussian!')
498
499         # grab and/or create the SPlot
500         if isinstance(splot, Spectrum):
501             splot = SPlot(splot, marker='k-', label='spectrum')
502
503         elif not isinstance(splot, SPlot):
504             raise ProfileError('FittingGUI() expects the 'splot' argument to '
505                                'either be a Spectrum or a SPlot!')
506
507         # -----
508         # if the profile 'function' is 'Voigt' and we have necessary parameters,
509         # show a preview for 'b' and 'N' and 'v'.
510         self.any_line_parameters = True if obs or ion else False
511         self.has_line_parameters = True if obs and ion else False
512         if self.any_line_parameters and not self.has_line_parameters:
513             raise ProfileError('From FittingGUI.__init__(), if the absorption line '
514                                'parameters 'obs' or 'ion' are provided, both must be given!')
515
516         if self.has_line_parameters:
517
518             if function != 'Voigt':
519                 raise ProfileError('From FittingGUI.__init__(), in order to compute the '
520                                    'broadening from the instrument profile of the 'obs'ervatory and the '
521                                    'column density for the 'ion', it is expected that we try to fit a 'Voigt' '
522                                    'profile 'function!')
523
524             if not isinstance(obs, Observatory):
525                 raise ProfileError('From FittingGUI.__init__(), if 'obs' is provided it should '
526                                    'be of type Observatory!')
527
528             if not hasattr(obs, 'resolution'):
529                 raise ProfileError('From FittingGUI.__init__(), if an observatory 'obs' is '
530                                    'provided, it needs to have a member 'resolution!')
531
532             if not hasattr(ion, 'wavelength') or not hasattr(ion.wavelength, 'unit'):
533                 raise ProfileError('From FittingGUI.__init__(), the provided 'ion' either '
534                                    'did not have a 'wavelength' attribute or it has one without units!')
535
536             if not hasattr(ion, 'fvalue'):
537                 raise ProfileError('From FittingGUI.__init__(), the provide 'ion' does not '
538                                    'have an 'fvalue' (oscillator strength) attribute!')
539
540             if hasattr(ion.fvalue, 'unit') and ion.fvalue.unit != u.dimensionless_unscaled:
541                 raise ProfileError('From FittingGUI.__init__(), the oscillator strength, '
542                                    ''fvalue' for an ion must be a dimensionless Quantity!')
543
544             if not hasattr(ion, 'A') or not ion.A:
545                 raise ProfileError('From FittingGUI.__init__(), the provided 'ion' does not '
546                                    'have an 'A' (transition probability) attribute!')
547
548             if hasattr(ion.A, 'unit') and ion.A.unit != u.Unit('s-1'):
549                 raise ProfileError('From FittingGUI.__init__(), the transition probability, '
550                                    ''A', from the 'ion' must be in units of 's-1' if units are present!')
551

```

```

552
553 # the instrument broadening is from  $R = \lambda / \Delta\lambda$ 
554 # FWHM = 2 * sqrt( 2 * log 2 ) * sigma for the Gaussian instrument profile
555 self.R = obs.resolution
556 self.sigma_instrument = (ion.wavelength / self.R) / (2 * np.sqrt(2 * np.log(2)))
557 self.sigma_instrument_squared = self.sigma_instrument.value ** 2
558
559 # save parameters for later
560 self.wavelength = ion.wavelength
561 self.fvalue = ion.fvalue
562 self.A = ion.A
563
564 # the FWHM of the intrinsic line profile (Lorentzian) is proportional to the
565 # transition probability (Einstein coeff.) 'A'...
566 # convert from km s-1 to wavelength units
567 self.gamma = (ion.wavelength * (ion.wavelength * ion.A / (2 * np.pi))).to(u.km / u.s) /
568 c.si).to(ion.wavelength.unit).value
569
570 # the leading constant in the computation of 'N' (per Angstrom per cm-2)
571 # self.leading_constant = (m_e.si * c.si / (np.sqrt(np.pi) * e.si**2 * ion.fvalue *
572 # ion.wavelength.to(u.Angstrom))).value
573 self.leading_constant = 1 / (ion.fvalue * ion.wavelength.to(u.AA)**2 * np.pi *
574 e.emu**2 / (m_e.si * c.to(u.km/u.s)**2)).value
575
576 # setting 'function' to 'ModifiedVoigt' only makes a change in how the 'Voigt'
577 # profile is evaluated by using 'self.gamma' instead of self.Params[...]['Gamma']
578 function = 'ModifiedVoigt'
579
580 # -----
581
582 print('\n We need to extract the lines from the continuum before we '
583 'begin the fitting process.')
584
585 # extract the line, continuum, rms from the spectrum
586 self.line, self.continuum = Extract(splot, bandwidth=bandwidth, kind=kind)
587 self.rms = self.continuum.rms
588
589 print('\n Now select the peaks of each line to be fit.')
590 print(' Initial guesses will be made for each line marked.')
591 input(' Press <Return> after making your selections ... ')
592
593 # grab all the selected points
594 global selected
595 points = np.array([
596     [ entry.value for entry in selected['wave'] ],
597     [ entry.value for entry in selected['data'] ]
598 ])
599
600 # point pairs in ascending order by wavelength
601 points = points[:, points[0].argsort()]
602
603 # domain size of the line and the number of components
604 self.domainsize = self.line.wave.value[-1] - self.line.wave.value[0]
605 self.numlines = np.shape(points)[1] - 4
606
607 if self.numlines < 1:
608     raise ProfileError('FittingGUI() expects at least one line to '
609 'be selected for fitting!')
610
611 # final spectral line profile is convolution of the LSP and the
612 # line profile function. Gaussian on Gaussian, Gaussian on Lorentzian,
613 # etc ... Set the functional form given requested profile function
614 self.Evaluate = self.SetFunction(function)
615
616 # initial guesses for parameters given the line locations,
617 # containing 'L1', 'L2', etc ... the values of which are themselves
618 # dictionaries of parameters (e.g., 'FWHM', 'Depth', etc...) whose values
619 # are the initial guesses for those parameters given the location of
620 # it's peak and the number of peaks within the 'line's domain.
621 self.Params = {
622
623     'L' + str(line + 1) : self.Parameterize(function, loc)
624     for line, loc in enumerate(points[:, 2:-2].T)
625
626 }
627
628 # grab the actual Figure object and it's axis to keep references
629 self.splot = splot
630 self.fig = splot.fig
631 self.ax = splot.ax
632
633 # refresh image, but keep any changes in axis limits
634 splot.xlim( *splot.ax.get_xlim() )
635 splot.ylim( *splot.ax.get_ylim() )
636 splot.draw()
637
638 # bring up plot to make room for sliders
639 plt.subplots_adjust(bottom = 0.30)
640
641 # resample continuum onto line domain
642 self.continuum = self.continuum.copy()
643 self.continuum.resample(self.line)

```

```

644
645 # common domain for plotting, strip units, wavelengths from continuum
646 self.x = self.continuum.wave.value
647 self.continuum = self.continuum.data.value
648
649 # copy of continuum allows for adjustments
650 self.y = self.continuum.copy()
651
652 # save the mid-level of the continuum to avoid over-calculation
653 self.continuum_level = self.continuum.mean()
654
655 # add plots of each line, keep dictionary of handles
656 self.Component = {
657
658     line : plt.plot(self.x,
659                     self.y - self.Evaluate(self.x, **parameters), 'k--')[0]
660
661     for line, parameters in self.Params.items()
662 }
663
664 # add plot of the continuum
665 self.Continuum, = plt.plot(self.x, self.y, 'r-', lw=2)
666
667 # add plot of superposition of each component
668 self.Combination, = plt.plot(self.x, self.y - self.SuperPosition(), 'g-')
669
670 # fix the limits on plot
671 xmin, xmax = splot.ax.get_xlim()
672 ymin, ymax = splot.ax.get_ylim()
673 plt.axis([xmin, xmax, ymin, ymax])
674
675 # axes for parameter sliders
676 self.Axis = {
677
678     # key : axis      xpos , ypos + dy      , xsize, ysize
679     line : plt.axes([0.10, 0.05 + (k+1) * 0.03, 0.65, 0.02], axisbg = 'white')
680     for k, line in enumerate( self.Params['L1'].keys() )
681 }
682
683 # add an axis to make adjustments to the continuum
684 self.Axis['Continuum'] = plt.axes([0.10, 0.05, 0.65, 0.02], axisbg='white')
685
686 # create the sliders for the parameters
687 self.Slider = {
688
689     # Slider 'key' and widget
690     param : widgets.Slider(
691
692         self.Axis[param], # which axis to put slider on
693         param, # name of parameter (and the slider)
694         self.Minimum(param), # set the minimum of the slider
695         self.Maximum(param), # set the maximum of the slider
696         valinit = self.Params['L1'][param] # initial value
697     )
698
699     # create a slider for each parameter
700     for param in self.Params['L1'].keys()
701 }
702
703 # create the slider for the continuum (10% adjustments)
704 self.Slider['Continuum'] = widgets.Slider(self.Axis['Continuum'], 'Continuum',
705     0.90 * self.continuum_level, 1.10 * self.continuum_level,
706     valinit = self.continuum_level)
707
708 # connect sliders to update function
709 for slider in self.Slider.values():
710     slider.on_changed(self.Update)
711
712 # create axis for radio buttons
713 self.RadioAxis = plt.axes([0.85, 0.01, 0.1, 0.2],
714     axisbg = 'white', frameon = False)
715
716 # create the radio button widget
717 self.Radio = widgets.RadioButtons(self.RadioAxis,
718     tuple(['L' + str(i+1) for i in range(self.numlines)]), active = 0)
719
720 # connect the radio button to it's update function
721 self.Radio.on_clicked(self.ToggleComponent)
722
723 # set current component as the first line
724 self.current_component = 'L1'
725
726 # make currently selected line bold
727 self.Component['L1'].set_linewidth(2)
728
729 # variable allows for the radio buttons to not screw-up the sliders/graphs
730 # when switching between lines
731 self.stall = False
732
733 # add the initial text for 'N' and 'b' if applicable.
734 # text is along 20% below the y-axis
735 if self.has_line_parameters:

```

```

736 # self.b, self.N, self.v = self.solve_b(), self.solve_N(), self.solve_v()
737 self.preview = self.ax.text(xmin, ymin - 0.1 * (ymax - ymin),
738                             'v: {:>10.4f} km s-1      b: {:>10.4f} km s-1'
739                             '      W: {:>10.4f}\nN: {:>10.4e} cm-2      tau_0: {:>10.4f}'.format(
740                             self.solve_v().value, self.solve_b().value, self.solve_W(), self.solve_N().value,
741                             self.solve_tau0(), va = 'top')
742
743 # display the text
744 self.fig.canvas.draw_idle()
745
746 def Parameterize(self, function, loc):
747     """
748     Choose the initial parameters of 'function' given the peak 'loc'.
749     """
750     if function == 'Voigt':
751         return {'Gamma': 0.10 * self.domainsize / self.numlines,
752                 'Sigma': 0.20 * self.domainsize / self.numlines, 'Peak': loc[0],
753                 'Depth': self.continuum[ loc[0] ].value - loc[1]}
754
755     if function == 'Lorentzian':
756         return {'FWHM': 0.5 * self.domainsize / self.numlines, 'Peak': loc[0],
757                 'Depth': self.continuum[ loc[0] ].value - loc[1]}
758
759     elif function == 'Gaussian':
760         return {'FWHM': 0.5 * self.domainsize / self.numlines, 'Peak': loc[0],
761                 'Depth': self.continuum[ loc[0] ].value - loc[1]}
762
763     elif function == 'ModifiedVoigt':
764         return {'Sigma': (self.Maximum('Sigma') - self.Minimum('Sigma'))/2,
765                 'Peak': loc[0], 'Depth': self.continuum[ loc[0] ].value - loc[1]}
766
767     else:
768         raise ProfileError('From FittingGUI.Parameterize(), the only '
769                             'currently implemented functions are the 'Gaussian', 'Lorentzian', and '
770                             ''Voigt' profiles!')
771
772 def SetFunction(self, function):
773     """
774     Return how to 'Evaluate' the profile given the 'function'.
775     """
776     options = {'Voigt': self.__Voigt, 'Lorentzian': self.__Lorentzian,
777               'Gaussian': self.__Gaussian, 'ModifiedVoigt': self.__ModifiedVoigt}
778
779     if function not in options:
780         raise ProfileError('From FittingGUI.SetFunction(), the only '
781                             'currently implemented functions are the 'Voigt', 'Lorentzian', and '
782                             ''the 'Gaussian' profiles!!')
783
784     return options[function]
785
786 def __Gaussian(self, x, **params):
787     """
788     A Gaussian profile. See ..Algorithms.Functions.Gaussian
789     """
790     return Gaussian(x, params['Depth'], params['Peak'], params['FWHM'] / 2.3548200450309493)
791
792 def __Lorentzian(self, x, **params):
793     """
794     A Lorentzian profile. See ..Algorithms.Functions.Lorentzian
795     """
796     return params['Depth'] * Lorentzian(x, params['Peak'], params['FWHM'])
797
798 def __Voigt(self, x, **params):
799     """
800     The Voigt profile. See ..Algorithms.Functions.Voigt
801     """
802     return Voigt(x, params['Depth'], params['Peak'], params['Sigma'], params['Gamma'])
803
804 def __ModifiedVoigt(self, x, **params):
805     """
806     This is the Voigt profile, but 'gamma' was already set.
807     """
808     return Voigt(x, params['Depth'], params['Peak'], params['Sigma'], self.gamma)
809
810 def SuperPosition(self):
811     """
812     Superposition of each line component (blended line)
813     """
814     combined = np.zeros(np.shape(self.x))
815     for parameters in self.Params.values():
816         combined += self.Evaluate(self.x, **parameters)
817     return combined
818
819 def Minimum(self, param):
820     """
821     Set the lower bound on the 'parameter' for its slider.
822     """
823     if param == 'Peak':
824         return self.x[0]
825
826     elif param == 'FWHM':
827         return 1e-6

```



```

828
829     elif param == 'Depth':
830         return 1e-6
831
832     elif param == 'Sigma':
833         if self.Evaluate != self.__ModifiedVoigt:
834             return 1e-6
835         else:
836             return self.sigma_instrument.value
837
838     elif param == 'Gamma':
839         return 1e-6
840
841     else:
842         raise ProfileError('From FittingGUI.Minimum(), '{}' is not '
843                             'currently implemented as a parameter to set the mininum '
844                             'for!'.format(param))
845
846     def Maximum(self, param):
847         """
848         Set the upper bound on the 'param'eter for its slider.
849         """
850         if param == 'Peak':
851             return self.x[-1]
852
853         elif param == 'FWHM':
854             return 0.9 * self.domainsize
855
856         elif param == 'Depth':
857             return 1.5 * self.continuum.max()
858
859         elif param == 'Sigma':
860             return 0.9 * self.domainsize / self.numlines
861
862         elif param == 'Gamma':
863             return 0.9 * self.domainsize / self.numlines
864
865         else:
866             raise ProfileError('From FittingGUI.Maximum(), '{}' is not '
867                                 'currently implemented as a parameter to set the maximum '
868                                 'for!'.format(param))
869
870     def Update(self, val):
871         """
872         Cycle thru Sliders and update Parameter dictionary. Re-draw graphs.
873         """
874         # 'self.stall' suppresses this procedure while inside 'ToggleComponent'
875         if not self.stall:
876             # the currently selected line component
877             line = self.current_component
878
879             # update the appropriate parameters in the dictionary
880             for parameter, slider in self.Slider.items():
881                 if parameter == 'Continuum':
882                     self.y = self.continuum + (slider.val - self.continuum_level)
883                 else:
884                     self.Params[line][parameter] = slider.val
885
886             # update the appropriate graph data, based on new parameters
887             for line, parameters in self.Params.items():
888                 self.Component[line].set_ydata(self.y - self.Evaluate(self.x, **parameters))
889
890             # update the continuum graph
891             self.Continuum.set_ydata(self.y)
892
893             # update the combined graph
894             self.Combination.set_ydata(self.y - self.SuperPosition())
895
896             # update the displayed 'N' and 'b' if present
897             if self.has_line_parameters:
898                 self.Update_Preview()
899
900             # push updates to graph
901             self.fig.canvas.draw_idle()
902
903     def ToggleComponent(self, label):
904         """
905         Toggle function for the radio buttons. Switch between line components
906         'L1', 'L2', etc. Update the sliders to reflect changing parameters.
907         """
908         # reassign the current component that is selected
909         self.current_component = label
910
911         # don't update the parameter dictionary or draw the graph!!!!!!
912         self.stall = True
913
914         # make current feature bold and the rest thin
915         for line in self.Component.keys():
916             if line == label:
917                 self.Component[line].set_linewidth(2)
918             else:

```

```

920         self.Component[line].set_linewidth(1)
921
922     # update the sliders to reflect the current component
923     for parameter, slider in self.Slider.items():
924         if parameter != 'Continuum':
925             slider.set_val(self.Params[label][parameter])
926
927     # update the displayed 'b', 'N' and 'z' if present
928     if self.has_line_parameters:
929         self.Update_Preview()
930
931     # give control back to sliders
932     self.stall = False
933
934     # push updates to graph
935     self.fig.canvas.draw_idle()
936
937     def solve_b(self):
938         """
939         Given the current line component, solve for the broadening parameter, 'b',
940         given the instrument profile and the observed broadening.
941         """
942         b = sqrt(2) * sigma_v
943         sigma_obs = self.Params[self.current_component]['Sigma']
944         sigma_v = np.sqrt(sigma_obs**2 - self.sigma_instrument_squared) * self.wavelength.unit
945         b = np.sqrt(2) * (c * sigma_v / self.wavelength)
946         return b.to(u.km / u.second)
947     # return (c.si * (1.4142135623730951 *
948         # np.sqrt(self.Params[self.current_component]['Sigma']**2
949         # - self.sigma_instrument_squared) * self.wavelength.unit) / self.wavelength).to(u.km /
950         # u.second)
951
952     def solve_tau0(self):
953         """
954         Solve for the apparent optical depth at line center.
955         """
956         line_data = self.Component[self.current_component].get_ydata()
957         line_wave = self.Component[self.current_component].get_xdata()
958         line_center = line_data.argmin()
959
960         return np.log(self.y[line_center] / line_data[line_center])
961
962     def solve_W(self):
963         """
964         Solve for the equivalent width of the currently selected line.
965         """
966         line_data = self.Component[self.current_component].get_ydata()
967         line_wave = self.Component[self.current_component].get_xdata()
968
969         # apparent optical depth
970         tau = np.log(self.y / line_data)
971         return Integrate(1 - np.exp(-tau), line_wave) * self.wavelength.unit
972
973     def solve_N(self):
974         """
975         Solve for the column density of the currently selected line component.
976         """
977         # equivalent width (dimensionless)
978         W = self.solve_W() / self.wavelength
979
980         # m_e c^2 / pi e^2 \approx 1.13e12 cm^-1 ??? How is that?
981         const = (1.13e12 / u.cm) / (self.fvalue * self.wavelength.to(u.cm))
982         return const * W
983
984     def solve_v(self):
985         """
986         Solve for the velocity of the line given the expected wavelength.
987         The result is returned in km s-1.
988         """
989         line_center = self.Params[self.current_component]['Peak'] * self.wavelength.unit
990         return c.to(u.km / u.second) * (line_center - self.wavelength) / self.wavelength
991
992     def Update_Preview(self):
993         """
994         Re-compute the 'b', 'N', and 'v' values, update the text in the plot.
995         """
996         # self.b, self.N, self.v = self.solve_b(), self.solve_N(), self.solve_v()
997         self.preview.set_text('v: {:>10.4f} km s-1 b: {:>10.4f} km s-1'
998                               ' W: {:>10.4f}\nN: {:>10.4e} cm-2 tau_0: {:>10.4f}'.format(
999             self.solve_v().value, self.solve_b().value, self.solve_W(), self.solve_N().value,
1000             self.solve_tau0()))
1001
1002     def GetSpectra(self):
1003         """
1004         Return the current graphs as Spectrum objects.
1005         """
1006         return [Spectrum(self.Component[line].get_ydata() * self.line.data.unit,
1007                          self.x * self.line.wave.unit) for line in sorted(self.Component.keys())]
1008
1009     def GetContinuum(self):
1010         """
1011         Return the current graph of the continuum.

```

```

1012     """
1013     continuum = Spectrum(self.y * self.line.data.unit, self.x * self.line.wave.unit)
1014     continuum.rms = self.rms
1015     return continuum
1016
1017 def kill(self):
1018     """
1019     Close the plot to destroy widgets and restore the 'splot' to its original state.
1020     """
1021     plt.close(self.fig)
1022     self.splot.fig = plt.figure("Spectral-Plot (SLiPy)")
1023     self.splot.ax = self.splot.fig.add_subplot(111)
1024     self.splot.draw()
1025     #del(self)
1026
1027 def MultiFit(splot, error=None, obs=None, ion=None, function='Voigt', measure=True,
1028             boost=None, **kwargs):
1029     """
1030     The MultiFit routine takes a 'splot' figure (type SPlot) and allows the
1031     user to interactively fit line profiles. 'splot' may optionally be of type
1032     Spectrum, in which case a SPlot figure will be created for you. This function
1033     creates a *FittingGUI* object (not documented here) which uses the Profile.Extract()
1034     routine first ('kwargs' are passed to this function). As in the Extract routine, the user
1035     will select four points that mark the boundaries of the line (blended or otherwise)
1036     and some surrounding continuum to sample. The KernelFit1D (..Algorithms.KernelFit) routine
1037     is applied with the user specified 'bandwidth' to smooth the noise out of the continuum
1038     and interpolate, of type 'kind', across the line gap. After this, the user is asked to
1039     further select points marking the peaks of the line(s). The number of selection points
1040     indicates the number of lines to be fit. If you wish to deblend two or more lines, select
1041     all suspected locations. These are not only used to determine the number of lines to fit
1042     but to make initial guesses at the parameters for each line and determine reasonable scales
1043     for the sliders.
1044
1045     After these selections, a slider for each parameter appears along with radio buttons for
1046     each line. The user can interactively adjust the parameter(s) for a given line by
1047     selecting it (the radio buttons) and dragging a slider. The parameters available to
1048     adjust depend on the 'function' argument. There are currently three available line shapes:
1049     'Gaussian', 'Lorentzian', and 'Voigt'. See ..Algorithms.Functions for information on
1050     these.
1051
1052     Each line is represented by a black, dashed curve in the plot. The currently selected line
1053     is bold. The combined (i.e., blended) line is plotted as a solid green curve.
1054
1055     If an Observatory with a 'resolution' is provided via the 'obs' argument then the
1056     thermal broadening parameter 'b' can be computed (and displayed). This is only applicable
1057     with either a 'Gaussian' or 'Voigt' profile. Further, an 'ion' needs to be provided in
1058     this scenario (type ..Data.Atomic.Ion) with an oscillator strength (fvalue), transition
1059     probability (A) and wavelength as members. With these data, we can interactively show
1060     the broadening parameter, the velocity, and the apparent column density during the fitting
1061     process. Note: the 'gamma' slider will disappear in this context because it has already
1062     been determined via the transition probability.
1063
1064     Each slider is labeled on the left side with the name of the parameter it controls. At
1065     the right of each slider is the current value of that parameter. The radio buttons are
1066     labeled "L1", "L2", etc. for each line.
1067
1068     This routine returns both a list of Spectrum 'lines' as well as the 'continuum' that was
1069     fit using the FittingGUI. This functions acts as both a single line fitting tool as well
1070     as a deblending tool. By default, the final parameterizations are attached to each spectrum
1071     as a dictionary, '.parameters'.
1072
1073     If 'measure' is passed as True (the default), the equivalent width is computed and attached
1074     to each spectrum ('L1', 'L2', etc...) and can be accessed with '.W'. If 'b' and/or 'N' are
1075     available for each line these will be attached as well, accessible as '.b' and '.N'
1076     respectively. This functionality can be suppressed by setting 'measure' to False. 'boost'
1077     and 'error' are passed to EquivalentWidth() and ColumnDensity().
1078     """
1079
1080     # running the user interface
1081     gui = FittingGUI(splot, obs=obs, ion=ion, function=function, **kwargs)
1082     input('\n Press <Return> when you are finished fitting lines ...')
1083
1084     # attach the parameter dictionaries to each spectrum
1085     lines = gui.GetSpectra()
1086     for a, parameterization in enumerate( sorted(gui.Params.keys()) ):
1087         lines[a].parameters = gui.Params[parameterization]
1088
1089     # attach the continuum to the line list
1090     continuum = gui.GetContinuum()
1091
1092     if not measure:
1093         return lines, continuum
1094
1095     if gui.has_line_parameters:
1096         for line, key in zip(lines, sorted(gui.Params.keys())):
1097             # set the line to 'L1', 'L2', etc...
1098             gui.current_component = key
1099             # attach the measured quantities
1100             notes = 'Measurement made using Profile.MultiFit() from SLiPy'
1101
1102             line.W = EquivalentWidth(line, continuum, error=error, boost=boost)
1103             line.N = ColumnDensity(line, continuum, ion, error=error, boost=boost)

```

```
1104         line.b = Measurement(gui.solve_b(), name='Doppler Broadening Paramater', notes=notes)
1105         line.v = Measurement(gui.solve_v(), name='Velocity', notes=notes)
1106
1107     gui.kill()
1108
1109     return lines, continuum
```

C.17 .. SLiPy . Simbad

```
1  #!/usr/bin/env python
2  # Copyright (c) Geoffrey Lentner 2015. All Rights Reserved.
3  # slipy/SLiPy/Simbad.py
4  """
5  usage: Simbad.py @Attribute <identifier> [**kwargs]
6
7  This module allows the user to query the SIMBAD astronomical database from
8  inside Python or shell commands/scripts.
9
10 The 'Attribute' points to a function within this module and indicates
11 what is to be run. Execute 'Simbad.py @Attribute help' for usage details of
12 a specific function. Currently available attributes are: 'Position',
13 'Distance', and 'Sptype'.
14
15 The identifier names can be anything recognized by SIMBAD (e.g., Regulus,
16 "alpha leo", "HD 121475", "del cyg", etc ...) if the name is two parts make
17 sure to use quotation to enclose it.
18
19 The **kwargs is the conventional reference to Python keyword arguments.
20 These should be specific to the 'Attribute' being pointed to.
21 """
22 from sys import argv, exit # , version_info
23 from urllib.request import urlopen
24
25 from astropy import units as u
26
27 from .. import SlipyError
28 from ..Framework.Command import Parse, CommandError
29 from ..Framework.Options import Options, OptionsError
30 from ..Framework.Measurement import Measurement
31
32
33 class SimbadError(SlipyError):
34     """
35     Exception specific to the Simbad module.
36     """
37     pass
38
39
40 def URLEncoded(url):
41     """
42     URLEncoded( string ):
43     Return a string with reserved url characters encoded.
44     """
45     # check argument type
46     if type(url) is not str:
47         raise SimbadError('URLEncoded function expects type str!')
48
49     # percent-encoded pair dictionary
50     encoded = {
51         '%': '%20',
52         '%': '%25',
53         '#': '%23',
54         '(': '%28',
55         ')': '%29',
56         '|': '%7c',
57         '+': '%2b'
58     }
59
60     return ''.join([
61         encoded[character] if character in encoded else character
62         for character in list(url)])
63
64
65 def Script(identifier, criteria):
66     """
67     Script( criteria ):
68
69     URL script for the SIMBAD astronomical database with added
70     URLEncoded(criteria).
71     """
72     script = [
73         'http://simbad.u-strasbg.fr/simbad/sim-script?',
74         'script=format%20object%20%22', URLEncoded(criteria),
75         '%22%0a', URLEncoded(identifier)
76     ]
77
78     return ''.join(script)
79
80
81 class Query:
82     """
83     Query( identifier, criteria, **kwargs ):
84
85     Class for querying the SIMBAD astronomical database for 'criteria'
86     of 'identifier'.
87
88     kwargs = {
89         'parse' : True, # extract relevant data from SIMBAD return file
```

```

90     'dtype' : float, # output datatype
91 }
92 """
93 def __init__(self, identifier, criteria, default=float, **kwargs):
94     """
95     Initiate query to SIMBAD database.
96     """
97     # check argument types
98     if type(identifier) is not str or type(criteria) is not str:
99         raise SimbadError('Simbad.Query function expects str'
100                             'types for arguments.')
101
102     try:
103         # keyword argument options for Query
104         self.options = Options( kwargs,
105                                 {
106                                     'parse' : True      , # parse SIMBAD return file
107                                     'full'  : False     , # return full line of info
108                                     'dtype' : default   , # convert return data
109                                     'is_main': False    , # called from Main()
110                                 })
111
112         # assignments
113         self.parse = self.options('parse')
114         self.full  = self.options('full')
115         self.dtype = self.options('dtype')
116         self.is_main = self.options('is_main')
117
118         # query SIMBAD database
119         with urlopen( Script(identifier, criteria) ) as response:
120             self.data = str( response.read().decode('utf-8') ).strip()
121
122     except OptionsError as err:
123         print('\n --> OptionsError:', err.msg )
124         raise SimbadError('Simbad.Query was not constructed '
125                             'for {}'.format(identifier))
126
127     except URLError as error:
128         raise SimbadError('Failed to contact SIMBAD database for'
129                             ' {}'.format(identifier) )
130
131     if 'not found' in self.data or 'error' in self.data:
132         raise SimbadError('{} could not be resolved by SIMBAD.'
133                             .format(identifier))
134
135     if self.parse:
136         # pre-parse operation common to all criteria
137         self.data = self.data.split('data')[-1]
138
139     def __call__(self):
140         """
141         Retrieve data from Query
142         """
143         return self.data
144
145     def Position( identifier, **kwargs ):
146         """
147         Position( identifier, **kwargs ):
148
149         Handle to the Query class with criteria='%C00(d;C)'.
150         """
151         query = Query( identifier, '%C00(d;C)', **kwargs )
152
153         if query.full:
154             query.data = query.data.split('\n')[-1]
155
156         elif query.parse:
157             # extract relevant data
158             query.data = query.data.split()[-1].split('+')
159             if len( query.data ) == 1:
160                 # dec had '-' not '+'
161                 query.data = query.data[0].split('-')
162                 query.data[1] = '-' + query.data[1]
163             # return formatted data type
164             query.data = [ query.dtype(pos) * u.degree for pos in query.data ]
165
166         if query.is_main:
167             if query.full or not query.parse:
168                 print( query() )
169             else:
170                 print('{0:.2f} {1:.2f}'.format(*query()))
171
172         else: return query.data
173
174     def Distance( identifier, **kwargs ):
175         """
176         Distance( identifier, **kwargs ):
177
178         Handle to the Query class with criteria='%PLX'
179         """
180         query = Query( identifier, '%PLX', **kwargs )
181

```

```

182     if query.full:
183         data = query.data.split('\n')[-1]
184
185     elif query.parse:
186
187         # extract relevant data
188         data = query.data.split()
189
190         if data[1] == '~':
191             # nothing found!
192             raise SimbadError('No distance found for {}'.format(identifier))
193         try:
194
195             # convert milli-arcseconds to parsecs
196             result = u.pc / ( query.dtype(data[1]) / 1000.0 )
197
198         except ValueError as err:
199             raise SimbadError('Use a numeric type for Simbad.Distance!')
200
201         if data[2][0] == '[' and data[2][-1] == ']':
202             # TODO: understand SIMBAD error format
203             # an uncertainty was given by SIMBAD
204             uncertainty = u.pc * 0.001 * query.dtype(data[1]) * query.dtype(data[2][1:-1]) / (
205                 0.001 * query.dtype(data[1]) )**2
206             # uncertainty = result * query.dtype(data[2][1:-1])
207             uncertainty = None
208
209         else: uncertainty = None
210
211     else: data = query.data
212
213     if query.is_main:
214         if query.full or not query.parse:
215             print( data )
216         else:
217             print( '{0:.2f}'.format( data ) )
218
219     elif not query.parse:
220         return data
221
222     else: return result
223
224     # Measurement(result, error=uncertainty, name='Distance',
225     # notes='Retrieved from SIMBAD database for {}'.format(identifier))
226
227 def Sptype(identifier, **kwargs):
228     """
229     Handle to the Query class with criteria='%SP'.
230     """
231     query = Query(identifier, '%SP', **kwargs)
232
233     if query.full:
234         # return last full line of query
235         query.data = query.data.split('\n')[-1]
236
237     elif query.parse:
238         # extract relevant data
239         query.data = query.data.split()[1]
240
241     if query.is_main:
242         print( query() )
243
244     else: return query()
245
246 def IDList(identifier, **kwargs):
247     """
248     Handle to the Query class with criteria='%IDLIST'.
249     With 'parse' = True, return a list of alternate IDs for
250     the 'identifier' provided.
251     """
252     query = Query(identifier, '%IDLIST', **kwargs)
253
254     if query.parse:
255         # extract relevant data
256         query.data = query.data.split(':')[1].strip().split('\n')
257
258     if query.is_main:
259         for line in query.data:
260             print(line)
261
262     else: return query()
263
264 def Main( clargs ):
265     """
266     Main function. See __doc__ for details.
267     """
268
269     if len(clargs) < 2:
270         # show usage
271         print( __doc__ )
272         return 0
273
274     # Available functions for execution

```

```

275     executable = {
276         'Distance' : Distance, # search for parsecs
277         'Position' : Position, # search for ra, dec
278         'Sptype' : Sptype, # search for spectral types
279         'IDList' : IDList # search for IDs
280     }
281
282
283     try:
284         # Parse command line arguments
285         function, args, kwargs = Parse( clargs[1:] )
286
287         if not args and not kwargs or args[0] == 'help':
288             # show function usage
289             print( executable[function].__doc__ )
290             return 0
291
292         # run execution
293         for identifier in args:
294             executable[function]( identifier, is_main=True, **kwargs )
295
296         return 0
297
298     except CommandError as err:
299         print( '--> CommandError:', err.msg )
300         return 1
301
302     except KeyError as key:
303         print( '--> {} was not a recognized function.'.format(key) )
304         return 1
305
306     except SimbadError as err:
307         # don't let uncaught self exception pass if from main.
308         print( '--> SimbadError:', err.msg )
309         return 1
310
311     except Exception as err:
312         print( '--> Unrecognized error with query for '{}' '.format(args[0]))
313         print( '--> Exception: {}'.format(err) )
314         return 1
315
316 if __name__ == '__main__':
317     # Main return 0 or 1
318     exit( Main( argv ) )
319
320

```

C.18 .. SLiPy . Telluric

```
1  # Copyright (c) Geoffrey Lentner 2015. All Rights Reserved.
2  # See LICENSE (GPLv3)
3  # slipy/SLiPy/Telluric.Py
4  """
5  Telluric - Corrections for atmospheric absorption lines.
6  """
7  import numpy as np
8  from astropy import units as u
9
10 from .. import SlipyError
11 from ..Framework.Options import Options, OptionsError
12 from ..Correlate import Xcorr, CorrelateError
13 from ..Spectrum import Spectrum, SpectrumError
14
15 class TelluricError(SlipyError):
16     """
17     Exception specific to the Telluric module.
18     """
19     pass
20
21 def Correct(spectrum, *calibration, **kwargs):
22     """
23     Correct(spectrum, *calibration, **kwargs):
24
25     Perform a telluric correction on 'spectrum' with one or more
26     'calibration' spectra. If more than one calibration spectrum is
27     provided, the one with the best fit after performing both a
28     horizontal cross correlation and a vertical amplitude fit is used.
29     The spectrum and all the calibration spectra must have the same
30     number of pixels (elements). If a horizontal shift in the calibration
31     spectra is appropriate, only the corresponding range of the spectrum
32     is divided out!
33
34     kwargs = {
35         lag : 25, # pixel shift limit for XCorr()
36         range:(0.5, 2.0, 151), # numpy.linspace for amplitude trials
37     }
38     """
39     try:
40         # default keyword arguments
41         options = Options( kwargs,
42             {
43                 'lag' : 25, # pixel shift limit for XCorr()
44                 'range':(0.5, 2.0, 151) # numpy.linspace for amplitude trials
45             })
46
47         # check arguments
48         if not calibration:
49             raise TelluricError('At least one 'calibration' spectrum '
50                                 'needs to be provided for Telluric.Correct().')
51
52         if type(spectrum) is not Spectrum:
53             raise TelluricError('Telluric.Correct() expects all arguments '
54                                 'of type Spectrum.')
55
56         for cal in calibration:
57             if type(cal) is not Spectrum:
58                 raise TelluricError('Telluric.Correct() expects all '
59                                     'arguments to be of type Spectrum.')
60             if spectrum not in cal:
61                 raise TelluricError('Telluric.Correct() expects the '
62                                     ''spectrum' domain to be equivalent to or at least '
63                                     'contained within each 'calibration' spectrum.')
64
65         if len(options('range')) != 3:
66             raise OptionsError('range' expects a tuple of length 3.)
67
68         # assign parameters
69         lag = options('lag')
70         amp = np.linspace( *options('range') )
71         trials = len(amp)
72         npix = len(spectrum)
73
74     except OptionsError as err:
75         print(' --> OptionsError:', err)
76         raise TelluricError('Inappropriate keyword arguments in '
77                             'Telluric.Correct().')
78
79     # quit if too big of a task
80     if trials*npix > 1e8:
81         raise TelluricError('Telluric.Correct() is programmed to quit '
82                             'if it detects a request to operate on matrices with more '
83                             'than 10**8 elements.')
84
85     # resample all the calibration spectra
86     for cal in calibration:
87         cal.resample(spectrum)
88
89     # find best XCorr and amplitude adjustment
```

```

90 best = None
91 for cal in calibration:
92     # best horizontal pixel shift
93     shift = Xcorr( spectrum, cal, lag=lag)
94     # build matrices with identical rows (len=npix-shift)
95     if shift < 0:
96         calmatrix = np.tile(cal.data[:shift], (trials, 1))
97         objmatrix = np.tile(spectrum.data[-shift:], (trials, 1))
98     elif shift > 0:
99         calmatrix = np.tile(cal.data[shift:], (trials, 1))
100         objmatrix = np.tile(spectrum.data[:-shift], (trials, 1))
101     else:
102         calmatrix = np.tile(cal.data, (trials, 1))
103         objmatrix = np.tile(spectrum.data, (trials, 1))
104     # amplitude matrix has identical columns
105     size = np.shape(calmatrix)[1]
106     ampmatrix = np.tile(amp, (size,1)).T
107     # remove units for dimensionless operations
108     calmatrix = calmatrix.value
109     objmatrix = objmatrix.value
110     # flip arrays for amplification
111     diff = objmatrix - (1 - (1 - calmatrix) * ampmatrix)
112     # compute the RMS for each trial
113     rmsvector = np.sqrt(( diff**2 ).sum(axis=1) / size)
114     if not best:
115         # if first pass, assign to 'best'
116         best = ( rmsvector.min(), rmsvector.argmin(), shift, cal )
117     elif rmsvector.min() < best[0]:
118         # this fit is better, save it to 'best'
119         best = ( rmsvector.min(), rmsvector.argmin(), shift, cal )
120 # results of calibration fitting
121 index = best[1] # amplitude
122 shift = best[2] # XCorr
123 cal = best[3] # which calibration spectrum
124 # we can't update an attribute...
125 update = spectrum.data.value
126 # divide spectrum
127 if shift < 0:
128     update[-shift:] /= 1 - (1 - cal.data[:shift].value) * amp[index]
129 elif shift > 0:
130     update[:-shift] /= 1 - (1 - cal.data[shift:].value) * amp[index]
131 else:
132     update /= 1 - (1 - cal.data.value) * amp[index]
133 # re-incorporate units
134 spectrum.data = update * u.Unit(spectrum.yunits)

```

C.19 .. SLiPy . Velocity

```
1  # Copyright (c) Geoffrey Lentner 2015. All Rights Reserved.
2  # See LICENSE (GPLv3)
3  # slipy/SLiPy/Velocity.py
4  """
5  Radial velocity corrections for 1D spectra.
6  """
7
8  from astropy.io import fits as pyfits
9  from astropy.constants import c
10 from astropy import units as u
11
12 from .. import SlipyError
13 from ..astrolibpy.astrolib.helcorr import helcorr
14 from .Fits import Find, RFind
15 from .Observatory import Observatory
16 from .Spectrum import Spectrum
17 from ..Framework.Options import Options, OptionsError
18 from ..Framework.Display import Monitor, DisplayError
19
20 class VelocityError(SlipyError):
21     """
22     Exception specific to the Velocity module
23     """
24     pass
25
26 def HeaderInfo( fpath ):
27     """
28     HeaderInfo( fpath ):
29
30     Helper function of IrafInput.
31
32     Return a formatted string containing the year, month, and day of
33     observation from the FITS file with name 'fpath', as well as the
34     universal time of observation and the right ascension and declination
35     of the target.
36     """
37     try:
38         with pyfits.open(fpath) as hdulist:
39             ra = ':'.join( hdulist[0].header['alpha'].split() )
40             dec = ':'.join( hdulist[0].header['delta'].split() )
41             date_obs = hdulist[0].header['date-obs']
42             date, UT = date_obs.split('T')
43             year, month, day = [ x.lstrip('0') for x in date.split('-') ]
44
45             info = '{:>5} {:>2} {:>2} {:>8} {:>11} {:>12}\n'.format(
46                 year, month, day, UT, ra, dec )
47
48     except IOError as error:
49         raise VelocityError('Failure in '{}' from HeaderInfo()'.format(fpath))
50
51     return info
52
53 def IrafInput( *files, **kwargs ):
54     """
55     IrafInput( *args, **kwargs ):
56
57     Build an input file for IRAF's rvcorrect task.
58
59     'files' should be a list of FITS file names to build the output table for.
60     The user can optionally specify a 'toplevel' directory to search
61     (recursively!) under fitting the 'pattern' (default=*.fits). This results
62     of this pattern search will be added to the list of file names in 'args'
63     (if any given).
64
65     kwargs = {
66         'toplevel' : '' , # search 'toplevel' directory for files
67         'pattern' : '*.fits', # files under 'toplevel' fitting 'pattern'
68         'recursive': False , # search recursively under 'toplevel'
69         'outfile' : ''      # write lines to file named 'outfile'
70     }
71     """
72     try:
73         # dictionary of options
74         options = Options( kwargs,
75             {
76                 'toplevel' : '' , # search 'toplevel' directory for files
77                 'pattern' : '*.fits', # files under 'toplevel' fitting 'pattern'
78                 'recursive': False , # search recursively under 'toplevel'
79                 'outfile' : ''      # write lines to file named 'outfile'
80             }
81         )
82
83         # convert options types
84         toplevel = options('toplevel')
85         pattern = options('pattern')
86         recursive = options('recursive')
87         outfile = options('outfile')
88
89         files = list(files)
```

```

90     if toplevel:
91         # search for files matching 'pattern'
92         find = RFind if recursive else Find
93         files += find( toplevel, pattern )
94
95     # get info from files
96     info = [ HeaderInfo(fpath) for fpath in files ]
97
98     if outfile:
99         with open( outfile, 'w' ) as fp:
100             fp.writelines( info )
101
102     return info
103
104 except OptionsError as err:
105     print( ' --> OptionsError:', err )
106     raise VelocityError( 'Failed to construct table information in '
107         'IraInput().' )
108
109 def HelioCorrect( obs, *spectra, **kwargs ):
110     """
111     Perform heliocentric velocity corrects on 'spectra' based on
112     'obs'ervatory information (longitude, latitude, altitude) and the
113     member attributes, ra (right ascension), dec (declination), and jd
114     (julian date) from the 'spectra'.
115     """
116     try:
117         # define function parameters
118         options = Options( kwargs,
119             {
120                 'verbose': False # display messages, progress
121             }
122         )
123
124         # assign parameters
125         verbose = options( 'verbose' )
126
127         # check 'obs' type
128         if not isinstance( type(obs), Observatory ):
129             raise VelocityError( 'HelioCorrect() expects its first argument to '
130                 'be derived from the Observatory class.' )
131         elif ( not hasattr( obs, 'latitude' ) or not hasattr( obs, 'longitude' ) or
132             not hasattr( obs, 'altitude' ) ):
133             raise VelocityError( 'HelioCorrect expects 'obs'ervatory to have '
134                 'all three: latitude, longitude, and altitude attributes.' )
135
136         # check 'spectra' arguments
137         for a, spectrum in enumerate( spectra ):
138             if type( spectrum ) is not Spectrum:
139                 raise VelocityError( 'HelioCorrect() expects all 'spectra' '
140                     'arguments to be of type Spectrum.' )
141             if not spectrum.ra or not spectrum.dec or not spectrum.jd:
142                 raise VelocityError( 'Spectrum {} lacks one or all of 'ra', '
143                     'dec', and 'jd'; from HelioCorrect().'.format( a ) )
144             if not hasattr( spectrum, 'ra', 'unit' ):
145                 raise VelocityError( 'From HelioCorrect(), in spectrum {}, '
146                     'ra' doesn't have units!'.format( a ) )
147             if not hasattr( spectrum, 'dec', 'unit' ):
148                 raise VelocityError( 'From HelioCorrect(), in spectrum {}, '
149                     'dec' doesn't have units!'.format( a ) )
150             if not hasattr( spectrum, 'jd', 'unit' ):
151                 raise VelocityError( 'From HelioCorrect(), in spectrum {}, '
152                     'jd' doesn't have units!'.format( a ) )
153
154         if verbose:
155             display = Monitor()
156             print( ' Running HelioCorrect on {} spectra ...'
157                 .format( len( spectra ) ) )
158
159         for a, spectrum in enumerate( spectra ):
160
161             # heliocentric velocity correction in km s^-1,
162             # the 'astrolibpy...helcorr' function doesn't work with units,
163             # so I convert to appropriate units and strip them.
164             hcorr = helcorr(
165                 obs.longitude.to( u.degree ).value,
166                 obs.latitude.to( u.degree ).value,
167                 obs.altitude.to( u.meter ).value,
168                 spectrum.ra.to( u.hourangle ).value,
169                 spectrum.dec.to( u.degree ).value,
170                 spectrum.jd.to( u.day ).value
171             ) [1] * u.km / u.second
172
173             # apply correction to wave vector,
174             # del[Lambda] / Lambda = del[V] / c
175             spectrum.wave -= spectrum.wave * hcorr / c.to( u.km / u.second )
176
177             # show progress if desired
178             if verbose: display.progress( a, len( spectra ) )
179
180         # finalize progress bar (erase)
181         if verbose: display.complete()

```

```

182
183     except OptionsError as err:
184         print(' --> OptionsError:', err)
185         raise VelocityError('Failed to perform HelioCorrect() task.')
186
187     except DisplayError as err:
188         print(' --> DisplayError:', err)
189         raise VelocityError('Exception from Display.Monitor in HelioCorrect().')
190
191
192 def BaryCorrect( obs, *spectra, **kwargs ):
193     """
194     Perform barycentric velocity corrects on 'spectra' based on
195     'obs'ervatory information (longitude, latitude, altitude) and the
196     member attributes, ra (right ascension), dec (declination), and jd
197     (julian date) from the 'spectra'.
198     """
199     try:
200         # define function parameters
201         options = Options( kwargs,
202             {
203                 'verbose': False # display messages, progress
204             })
205
206         # assign parameters
207         verbose = options('verbose')
208
209         # check 'obs' type
210         if not isinstance( type(obs), Observatory):
211             raise VelocityError('HelioCorrect() expects its first argument to '
212                 'be derived from the Observatory class.')
213         elif ( not hasattr(obs, 'latitude') or not hasattr(obs, 'longitude') or
214             not hasattr(obs, 'altitude') ):
215             raise VelocityError('HelioCorrect expects 'obs'ervatory to have '
216                 'all three: latitude, longitude, and altitude attributes.')
217
218         # check 'spectra' arguments
219         for a, spectrum in enumerate(spectra):
220             if type(spectrum) is not Spectrum:
221                 raise VelocityError('HelioCorrect() expects all 'spectrum' '
222                     'arguments to be of type Spectrum.')
223             if not spectrum.ra or not spectrum.dec or not spectrum.jd:
224                 raise VelocityError('Spectrum {} lacks one or all of 'ra', '
225                     'dec', and 'jd'; from HelioCorrect().'.format(a))
226
227         if verbose:
228             display = Monitor()
229             print(' Running HelioCorrect on {} spectra ...'
230                 .format(len(spectra)))
231
232         for a, spectrum in enumerate(spectra):
233             # heliocentric velocity correction in km s^-1,
234             # the 'astrolibpy...helcorr' function doesn't work with units,
235             # so I convert to appropriate units and strip them.
236             hcorr = helcorr(
237                 obs.longitude.to(u.degree).value,
238                 obs.latitude.to(u.degree).value,
239                 obs.altitude.to(u.meter).value,
240                 spectrum.ra.to(u.hourangle).value,
241                 spectrum.dec.to(u.degree).value,
242                 spectrum.jd.to(u.second).value
243             )[0] * u.Unit('km s^-1')
244
245             # apply correction to wave vector,
246             # del[Lambda] / Lambda = del[V] / c
247             spectrum.wave -= spectrum.wave * hcorr / c
248
249             # show progress if desired
250             if verbose: display.progress(a, len(spectra))
251
252         # finalize progress bar (erase)
253         if verbose: display.complete()
254
255     except OptionsError as err:
256         print(' --> OptionsError:', err)
257         raise VelocityError('Failed to perform HelioCorrect() task.')
258
259     except DisplayError as err:
260         print(' --> DisplayError:', err)
261         raise VelocityError('Exception from Display.Monitor in HelioCorrect().')
262
263

```

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