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MILKY WAY RED DWARFS IN THE BoRG SURVEY; GALACTIC SCALE-HEIGHT AND THE DISTRIBUTION OF DWARF STARS IN WFC3 IMAGING

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ABSTRACT

We present a tally of Milky Way late-type dwarf stars in 68 Wide Field Camera 3 (WFC3) pure-parallel fields (227 arcmin²) from the Brightest of Reionizing Galaxies survey for high-redshift galaxies. Using spectroscopically identified M-dwarfs in two public surveys, the Cosmic Assembly Near-IR Deep Extragalactic Legacy Survey and the Early Release Science mosaics, we identify a morphological selection criterion using the half-light radius (r_{50}), a near-infrared $J - H$, $G - J$ color region where M-dwarfs are found, and a $V - J$ relation with M-dwarf subtype. We apply this morphological selection of stellar objects, color-color selection of M-dwarfs, and optical-near-infrared color subtyping to compile a catalog of 274 M-dwarfs belonging to the disk of the Milky Way with a limiting magnitude of $m_{F125W} < 24(AB)$. Based on the M-dwarf statistics, we conclude that (1) the previously identified north-south discrepancy in M-dwarf numbers persists in our sample; there are more M-dwarfs in the northern fields on average than in southern ones, (2) the Milky Way's single disk scale-height for M-dwarfs is 0.3–4 kpc, depending on subtype, (3) the scale-height depends on M-dwarf subtype with early types (M0–4) high scale-height ($z_0 = 3$ –4 kpc) and later types M5 and above in the thin disk ($z_0 = 0.3$ –0.5 kpc), (4) a second component is visible in the vertical distribution, with a different, much higher scale-height in the southern fields compared to the northern ones. We report the M-dwarf component of the Sagittarius stream in one of our fields with 11 confirmed M-dwarfs, seven of which are at the stream's distance. In addition to the M-dwarf catalog, we report the discovery of 1 T-dwarfs and 30 L-dwarfs from their near-infrared colors. The dwarf scale-height and the relative low incidence in our fields of L- and T-dwarfs in these fields makes it unlikely that these stars will be interlopers in great numbers in color-selected samples of high-redshift galaxies. The relative ubiquity of M-dwarfs however will make them ideal tracers of Galactic halo substructure with *EUCLID* and reference stars for *James Webb Space Telescope* observations.

Key words: Galaxy: disk – Galaxy: fundamental parameters – Galaxy: halo – Galaxy: structure – stars: low-mass

Online-only material: color figures, machine-readable table

1. INTRODUCTION

Counting stars to infer the shape and size of our Milky Way Galaxy is a classic experiment in astronomy. However, it is also among the most prone to insufficient data as well as conceptual shortfalls (e.g., Herschel 1785; Kapteyn 1922). Over time, it was established that the Milky Way's scale-height is inversely proportional to the masses of stars sampled (Gilmore & Reid 1983; Gilmore 1984; Siegel et al. 2002). Initially, many of the Galactic models were focused on relatively luminous giant stars and rarely addressed (sub)stellar objects due to completeness issues (see for reviews of star counts and Galactic structure; Bahcall 1986; Gilmore et al. 1989; King et al. 1990; Majewski 1993).

Interest has now shifted to the spatial distribution of (sub)stellar objects, in part because they are possibly the most significant interlopers in studies of extremely high redshift objects (see, e.g., Caballero et al. 2008), but also because these are physically some of the longest-lived objects. Consequently, any deep high-redshift survey, especially in the near-infrared, undertaken with the *Hubble Space Telescope* (*HST*) automati-

cally becomes a census of the smallest Milky Way stars. More importantly, these objects constitute the most numerous and oldest population of stars in the Galactic disk. For instance, Pirzkal et al. (2005) determined the scale-height of different types of dwarfs from the Hubble Ultra Deep Field (HUDF; Beckwith et al. 2006). Ryan et al. (2005) found L- and T-dwarfs in a small set of Advanced Camera for Surveys (ACS) parallel observations. Stanway et al. (2008) and Pirzkal et al. (2009) determined the Galactic scale-height of M-dwarfs from the Great Observatories Origins Deep Survey (GOODS) fields (Giavalisco et al. 2004). Ryan et al. (2011) added a search of early WFC3 pure-parallel fields for L- and T-dwarfs. These studies gradually improved statistics on L-, T-, and M-dwarfs to several dozens of objects.

The identification of these Galactic dwarfs in images is difficult because one needs both high-quality data to distinguish from extragalactic sources and a good understanding of the initial mass function or the local density of these objects as a class. Two of the above studies (Pirzkal et al. 2005, 2009) benefited from spectroscopic identification of the dwarf subtype in the *HST*/ACS grism spectra of the HUDF and GOODS fields

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Table 1

The Scale-heights for the Thin Disk of Dwarf Stars from the Literature

Milky Way Scale Height (z_0) (pc)	Reference	Type Stars
300	Zheng et al. (2001)	
400 ± 100	Pirzkal et al. (2005)	
350 ± 50	Ryan et al. (2005)	L, T dwarfs
370 ± 65	Pirzkal et al. (2009)	M4–M9 dwarfs
300 ± 70	Pirzkal et al. (2009)	M0–M9 dwarfs
$300 \pm 25 \pm 31$	Ryan et al. (2011)	>M8

(the GRAPES⁸ and PEARS⁹ projects, respectively). Combined with an index of stellarity in the direct image, this made identification of the dwarfs nearly certain. Alternatively, Kilic et al. (2005) used high-precision proper motion to identify the Galactic objects. Once an object has been identified as a candidate dwarf, its luminosity distance must be estimated, which requires accurate (sub)typing. Without direct spectra, we will show that this can be readily achieved with sufficient color coverage from the optical to the near-infrared. A dwarf census including subtype and distance can answer several outstanding issues regarding the shape of the Milky Way traced by its most numerous stellar members.

Pirzkal et al. (2009) found, like Stanway et al. (2008), an odd discrepancy in the number of M-dwarfs: there are 24% more M-dwarfs in the northern than in the southern GOODS field. Because our vantage point in the Milky Way is above the plane of the disk, one would expect the southern GOODS fields to have more M-dwarfs. However, at present, this discrepancy has only been determined from two sight-lines out of the Galaxy, so it is still possible this may be source count field-to-field variance. By studying the older stellar population content of our Galaxy along many sight-lines down to the faintest possible magnitude, we can directly observe and measure the shape of the thin Galactic disk as traced by the old stellar population.

In order to improve our understanding of the contribution of faint dwarfs to Galactic structure, we will need greatly improved statistics to compare against Milky Way structure models. We use the recent *HST*/WFC3 pure-parallel searches for bright high-redshift galaxies to find Milky Way dwarfs and determine the parameters of their distribution in the Milky Way disk (Trenti et al. 2011; Yan et al. 2010; Bradley et al. 2012). Thus far, based on *HST* imaging, the disk scale-height for dwarfs has been found to be 300 pc (Table 1): (Zheng et al. 2001), 400 ± 100 pc (Pirzkal et al. 2005), 350 ± 50 pc, (L, T dwarfs Ryan et al. 2005), 370 ± 65 pc (for M4–M9 dwarfs), and 300 ± 70 pc (for M0–M9 dwarfs, Pirzkal et al. 2009) and $300 \pm 25 (\pm 31 \text{ systematic})$ pc (>M8, Ryan et al. 2011).

The goal of this paper is to explore the reality of the north–south difference in M-dwarf counts and to accurately determine the scale-height of our Milky Way as traced by M-dwarfs. Previously, Ryan et al. (2011) investigated the L- and T-dwarf content; here we focus our analysis on the M-dwarfs.

The paper is organized as follows: Section 2 reports the properties of the *HST*/WFC3 observations we use. Section 3 discusses how we generate the relevant SEXTRACTOR catalogs. Section 4 presents our observational calibration of morphological identification of stars, M-dwarfs specifically, and subsequent subtyping of the M-dwarfs. Section 5 presents our catalog of

Table 2

Summary of the WFC3 Observations of BoRG, CANDELS (v0.5), and ERS on GOODS-S

	BoRG	CANDELS	ERS
Filters	<i>F125W</i> , <i>F160W</i> , <i>F098M</i> , <i>F606W</i> (<i>F600L</i>)	<i>F125W</i> <i>F160W</i>	<i>F125W</i> <i>F160W</i> <i>F098M</i>
Pixelscale	0".08	0".06 (resampled to 0".08)	0".08
Point Spread Function (PSF)	0".12	0".12	0".12
Exposure times (s)			
<i>F125W</i>	700–5100	1000	5017.61
<i>F160W</i>	500–3900	1050	5017.61

dwarfs in the Brightest of Reionizing Galaxies (BoRG) fields and briefly discusses the validity of our morphological selection. In Section 6 we discuss the north–south difference, the Galactic scale-height as a function of dwarf subtype. Section 7 lists our conclusions and outlines future work.

2. WFC3 OBSERVATIONS

We use three WFC3 data sets for this project: the Cosmic Assembly Near-IR Deep Extragalactic Legacy Survey (CANDELS) public v0.5 data release and the Early Release Science (ERS) mosaic, both in the GOODS-South (GOODS-S) field for calibration and characterization of known M-dwarfs, and the BoRG pure-parallel observations for the detection of new Galactic M-dwarfs.

2.1. CANDELS GOODS-S Observations

The CANDELS (Grogin et al. 2011; Koekemoer et al. 2011) is designed to explore galaxy evolution, from redshift $z = 1.5$ to ~ 8 . The survey is designed to cover approximately 800 arcmin² and is divided into two parts: the CANDELS/Deep survey on both GOODS-N and GOODS-S and CANDELS/Wide covering GOODS as well as the Extended Groth Strip (EGS), COSMOS, and UltraDeep Survey (UDS) fields. Data from the survey are nonproprietary and are published in a series of data releases as soon as reduced to scientific quality (see <http://candels.ucolick.org>). In this paper we use the v0.5 data release of the GOODS-South field, the first epoch of the CANDELS/Deep survey. Exposure times and sensitivity are very similar for this initial mosaic to the BoRG pure-parallel observations (Table 2) in the two near-infrared channels (*F125W* and *F160W*). We resampled the CANDELS *F125W* and *F160W* mosaics to a pixel scale of 0".08 using DRIZZLE (Fruchter & Hook 2002) to conform to the BoRG standard. For subsequent analysis, we only use a subsection of this field (Figure 1), where PEARS and CANDELS coverage overlap.

2.2. Early Release Science WFC3 Mosaic in Goods-South

The WFC3 imaging of the GOODS-S field is from the ERS (Windhorst et al. 2011) (see the footprint information at http://candels.ucolick.org/survey/tile_maps/GOODS-S.html and Figure 1). The 10 WFC3 fields in the ERS program were also imaged with the *F125W*, *F160W* and *F098M* filters, the reason it was included in the Ryan et al. (2011) sample. We retrieved the data from the Hubble Legacy Archive (www.hla.stsci.edu) and combined these into a mosaic using SWARP (<http://www.astromatic.net/software/swarp>) to the

⁸ Grism ACS Program for Extragalactic Science, see Pirzkal et al. (2004).

⁹ Probing Evolution And Reionization Spectroscopically, see Pirzkal et al. (2009).

Figure 1. GOODS-South field with the CANDELS v0.5 data release of the deep part of the survey (red) and the Early Release Science mosaics (blue) overlaid on a digital sky survey image. The black circles mark the PEARS-identified stars.

(A color version of this figure is available in the online journal.)

same pixel scale as the BoRG fields. Figure 1 shows the overlap of this mosaic with the PEARS-S survey (Pirzkal et al. 2009).

2.3. BoRG

Our principal data set is the WFC3 data from the BoRG (HST GO/PAR-11700; Trenti et al. 2011; Bradley et al. 2012) survey to identify Milky Way dwarf stars from their morphology and color. The BoRG observations are undithered *HST*/WFC3 conducted in pure-parallel with the telescope pointing to a primary spectroscopic target with the Cosmic Origin Spectrograph (COS; typically a high- z QSO at high Galactic latitude). The limitations for such observations are primarily that no dithering strategy can be used (final images are at WFC3 native pixel scale) and total exposure times are dictated by the primary program.

The program's initial aims were to obtain 176 arcmin^2 of sky in 38 pointings, using four WFC3 filters ($F606W$, $F098M$, $F125W$, and $F160W$). An extension of the BoRG program in Cycle-19 brought more parallel observations, and the full reproduced set of 68 images is presented in Bradley et al. (2012). Because lines of sight are independent and well separated on the sky mostly at high Galactic latitudes ($|b| > 20^\circ$, see Figure 2), the BoRG survey samples the Milky Way disk away from the plane better than single sight-lines (e.g., the GOODS or H(U)DF fields). The BoRG data set used here is the second data release of 68 WFC3 fields (Table 3) for a total of approximately 209.9 arcmin^2 as described in detail by Trenti et al. (2011) and Bradley et al. (2012), including some reprocessed fields from another pure-parallel program with similar science goals (Hubble Infrared Pure Parallel Imaging Extragalactic Survey, HIPPIES, HST GO/PAR-11702, Yan et al. 2010). We use the WFC3 data products generated by the BoRG team (see for details Bradley et al. 2012). This is a standard multidrizzle

Figure 2. Position of the 68 unique WFC3 pure-parallel fields in Galactic coordinates (red squares). The sampling of the Milky Way disk structure of substellar objects is much better than the two lines of sight by the GOODS/PEARS fields (black circles). We discard one field (borg_1815-3244) for its low latitudes and its line of sight through the plane of the disk and close to the center of the bulge.

(A color version of this figure is available in the online journal.)

Figure 3. Distribution of limiting magnitude in the $F125W$ filter from Bradley et al. (2012). Photometric detections are reliable down to 26 mag.

reduction of these undithered WFC3 data with Laplacian edge detection (van Dokkum 2001) to the individual flight (FLT) files to mitigate detector hot pixels and cosmic rays. Stellar objects are not affected by this filtering.

The BoRG survey is designed to identify relatively bright ($m_{F125W} \leq 27$) high-redshift galaxies from their broadband colors using the Lyman-break technique (Steidel et al. 1996). The primary aim of the survey is to select redshift $z \sim 7.5$ galaxies as $F098M$ dropouts. Two near-infrared filters ($F125W$ and $F160W$) are used for source detection and characterization down to 26 mag (Figure 3). One optical filter ($F606W$ or $F600LP$ in the case of the HIPPIES survey) is used to control contamination from lower redshift sources: $z \sim 1.5$ compact galaxies, active galactic nuclei (AGNs), and cool Milky Way stars. Our interest here now goes to the latter of these interlopers. Given the near-random pointing nature of the pure-parallel *HST*

Table 3
Basic Data for the BoRG Fields of the Second Data Release from Bradley et al. (2012) and Schmidt et al. (2014)

Field	Exptime (s)	Area (arcmin ²)	R.A. (J2000)	Decl. (J2000)	<i>l</i> (°)	<i>b</i> (°)	<i>z</i> _p (mag)	<i>z</i> _{p,lin} (mag)	Lim Mag	<i>E</i> (<i>B</i> − <i>V</i>)	<i>A</i> _{F098M}	<i>A</i> _{F125W}	<i>A</i> _{F160W}	<i>A</i> _{F606W}	<i>A</i> _{F600LP}
borg_0110-0224	13538.2	10.9	17.531664	−2.395226	133.978373	−64.865306	26.2	26.2	26.9	0.046	0.060	0.041	0.029	0.140	0.104
borg_0214+1255	1402.9	3.8	33.409984	12.915292	152.017684	−45.263536	26.2	26.1	25.9	0.122	0.158	0.109	0.077	...	0.273
borg_0228-4102	1402.9	3.7	36.986588	−41.025888	254.161019	−65.793327	26.2	26.2	26.8	0.015	0.019	0.013	0.009	...	0.033
borg_0240-1857	1402.9	3.6	40.114070	−18.953931	200.647911	−63.687697	26.2	26.2	26.7	0.033	0.043	0.030	0.021	...	0.074
borg_0427+2538	702.9	4.3	66.690208	25.640444	172.153535	−16.034094	26.2	25.4	25.1	0.906	1.173	0.809	0.574	...	2.031
borg_0436-5259	2905.9	3.2	69.059214	−52.986412	261.052355	−41.464289	26.2	26.2	27.3	0.007	0.009	0.006	0.004	...	0.015
borg_0439-5317	3005.9	3.3	69.855420	−53.278154	261.335374	−40.946634	26.2	26.2	27.2	0.005	0.006	0.004	0.003	...	0.011
borg_0440-5244	2002.9	3.4	69.958786	−52.731210	260.606945	−40.966425	26.2	26.2	27.0	0.006	0.008	0.006	0.004	...	0.014
borg_0540-6409	2308.8	1.4	84.879133	−64.150953	273.650789	−32.015266	26.2	26.2	26.6	0.057	0.074	0.051	0.036	0.172	...
borg_0553-6405	2611.7	1.7	88.275723	−64.088263	273.525627	−30.535388	26.2	26.2	26.8	0.045	0.059	0.040	0.029	0.137	...
borg_0624-6432	1205.9	3.2	95.897657	−64.528319	274.231122	−27.261687	26.2	26.2	26.4	0.058	0.075	0.052	0.037	0.174	...
borg_0640-6440	1205.9	3.2	95.950899	−64.662581	274.384073	−27.253871	26.2	26.2	26.6	0.059	0.076	0.053	0.037	0.178	...
borg_0637-7518	2411.7	5.0	99.265244	−75.312608	286.420817	−27.079824	26.2	26.2	26.6	0.101	0.131	0.090	0.064	0.305	...
borg_0751+2917	5114.7	3.5	117.709478	29.281998	191.357531	24.959335	26.2	26.2	27.1	0.043	0.055	0.038	0.027	0.129	0.096
borg_0756+3043	1905.9	3.3	118.988521	30.717701	190.217249	26.453514	26.2	26.2	26.6	0.062	0.081	0.056	0.040	0.189	...
borg_0840+3946	2205.9	3.4	122.089304	39.758799	180.921586	31.128951	26.2	26.2	26.6	0.045	0.059	0.040	0.029	0.137	...
borg_0819+4911	1205.9	3.9	124.830368	49.183970	170.094798	34.245407	26.2	26.2	26.5	0.051	0.066	0.046	0.032	0.155	...
borg_0820+2332	702.9	3.9	125.013578	23.535374	199.823057	29.325880	26.2	26.2	26.1	0.045	0.058	0.040	0.029	0.136	...
borg_0835+2456	2205.9	3.7	128.820679	24.936409	199.532045	33.060979	26.2	26.2	26.7	0.030	0.039	0.027	0.019	0.090	...
borg_0846+7654	2002.9	3.4	131.592805	76.893333	136.609253	32.760391	26.2	26.2	27.1	0.023	0.030	0.021	0.015	...	0.052
borg_0906+0255	2708.8	3.6	136.405132	2.925182	226.847796	30.959816	26.2	26.2	27.0	0.031	0.040	0.027	0.019	0.092	...
borg_0909+0002	1805.9	3.6	137.286275	−0.029911	230.317128	30.193272	26.2	26.2	26.7	0.031	0.040	0.027	0.019	0.093	...
borg_0914+2822	2205.9	3.5	138.569416	28.361907	198.147524	42.355253	26.2	26.2	26.8	0.025	0.032	0.022	0.016	0.076	...
borg_0922+4505	2105.9	3.7	140.406384	45.087611	175.139682	44.898070	26.2	26.2	26.5	0.020	0.026	0.018	0.013	0.060	...
borg_0926+4000	1105.9	4.0	141.392945	40.005560	182.318366	45.875115	26.2	26.2	26.2	0.015	0.020	0.014	0.010	0.046	...
borg_0926+4426	1602.9	3.7	141.382123	44.426101	175.988847	45.646771	26.2	26.2	26.7	0.016	0.020	0.014	0.010	...	0.035
borg_1010+3001	3211.7	3.8	152.405996	30.018416	198.478129	54.538030	26.2	26.2	26.8	0.024	0.032	0.022	0.015	0.074	...
borg_1014+0423	1105.9	3.3	153.523466	−4.378731	246.512301	40.657070	26.2	26.2	26.2	0.036	0.046	0.032	0.023	...	0.080
borg_1031+3804	1505.9	3.8	157.715302	38.058891	183.562795	58.661992	26.2	26.2	26.3	0.014	0.018	0.012	0.009	0.041	...
borg_1031+5052	4811.7	4.4	157.690654	50.861755	161.556783	54.378702	26.2	26.2	27.1	0.011	0.015	0.010	0.007	0.035	...
borg_1033+5051	3211.7	4.5	158.212380	50.859570	161.288017	54.668744	26.2	26.2	26.8	0.015	0.020	0.014	0.010	0.046	...
borg_1051+3359	3317.6	3.2	162.822134	33.985372	190.638764	63.346845	26.2	26.2	27.0	0.026	0.033	0.023	0.016	0.078	...
borg_1103-2330	4411.7	3.5	165.807563	−23.506099	273.102916	33.023056	26.2	26.2	27.2	0.063	0.082	0.056	0.040	0.191	...
borg_1111+5545	2605.9	3.2	167.736508	55.750992	148.327174	56.140872	26.2	26.2	27.0	0.017	0.022	0.015	0.011	0.052	...
borg_1119+4026	1402.9	3.7	169.513804	40.397987	172.408816	66.608159	26.2	26.2	26.8	0.016	0.020	0.014	0.010	...	0.035
borg_1131+3114	1402.9	3.7	172.876206	31.289335	194.731674	72.096104	26.2	26.2	26.8	0.023	0.029	0.020	0.014	...	0.051
borg_1152+5441	2808.8	3.5	177.958339	54.684118	140.431973	60.372656	26.2	26.2	27.1	0.010	0.013	0.009	0.006	0.030	...
borg_1153+0056	2208.8	3.6	178.182290	0.931268	272.226679	60.255130	26.2	26.2	26.7	0.022	0.028	0.019	0.014	0.066	...
borg_1209+4543	3708.8	3.6	182.54635	45.723905	144.365550	69.616030	26.2	26.2	27.2	0.014	0.018	0.013	0.009	0.043	...
borg_1230+0750	1805.9	0.5	187.469950	7.825175	287.119671	70.032220	26.2	26.2	26.0	0.024	0.031	0.021	0.015	0.072	...
borg_1242+5716	2508.8	3.5	190.553698	57.270437	125.411526	59.813474	26.2	26.2	26.9	0.009	0.012	0.008	0.006	...	0.021
borg_1245+3356	1505.9	3.8	191.186033	33.935834	134.469175	83.041931	26.2	26.2	26.7	0.016	0.021	0.015	0.010	0.049	...
borg_1301+0000	1602.9	3.7	195.317726	−0.007321	308.309140	62.761637	26.2	26.2	26.1	0.025	0.033	0.023	0.016	...	0.057
borg_1337+0028	1202.9	3.7	204.202249	−0.463529	326.341939	60.329542	26.2	26.2	26.6	0.030	0.039	0.027	0.019	...	0.067
borg_1341+4123	3205.9	3.3	205.130683	41.384472	90.818133	72.544121	26.2	26.2	27.2	0.007	0.009	0.006	0.004	...	0.015
borg_1408+5503	2611.8	3.5	211.992568	55.055640	101.682613	58.802067	26.2	26.2	26.9	0.014	0.018	0.012	0.009	0.042	...
borg_1437+5043	2508.8	3.6	219.233553	50.718933	89.759393	59.068028	26.2	26.2	27.0	0.013	0.016	0.011	0.008	0.038	...
borg_1524+0954	1602.9	3.5	231.040910	9.905686	14.750963	50.138306	26.2	26.2	26.5	0.042	0.055	0.038	0.027	...	0.095
borg_1555+1108	2908.8	3.4	238.856610	11.131677	21.791448	44.001085	26.2	26.2	27.0	0.052	0.068	0.047	0.033	0.158	...
borg_1632+3733	2405.9	3.5	248.074403	37.557004	60.247231	42.879109	26.2	26.2	27.0	0.010	0.014	0.009	0.007	0.032	...
borg_1632+3737	1205.9	3.5	247.891785	37.608886	60.304175	43.027091	26.2	26.2	26.6	0.010	0.013	0.009	0.006	0.029	...
borg_2057-4412	1202.9	3.5	314.340154	−44.206786	356.583873	−40.623775	26.2	26.2	26.4	0.038	0.049	0.034	0.024	...	0.085
borg_2132+1004	1005.9	3.8	323.061958	10.063711	63.564901	−29.075332	26.2	26.2	26.4	0.040	0.052	0.036	0.026	...	0.090
borg_2155-4411	1402.9	3.7	328.812024	−44.176682	355.248970	−50.945449	26.2	26.2	26.7	0.013	0.016	0.011	0.008	...	0.028
borg_2203+1851	2005.9	3.4	330.704916	18.850050	76.655821	−28.494164	26.2	26.2	26.8	0.069	0.090	0.062	0.044	...	0.155
borg_2345+0054	1402.9	3.8	356.260909	−0.901806	88.898069	−59.313470	26.2	26.2	26.8	0.036	0.047	0.033	0.023	...	0.082
borg_2351-4332	4208.8	3.1	357.650020	−43.525127	335.847122	−69.508926	26.2	26.2	27.3	0.013	0.017	0.011	0.008	...	0.029
borg_0456-2203	1809.0	3.1	73.964600	−22.048900	222.025278	−34.734134	26.2	26.3	26.7	0.038	0.037	0.028	0.020	0.095	...
borg_0951+3304	2212.0	1.8	147.700300	33.073700	192.933397	50.779624	26.2	26.3	26.5	0.013	0.013	0.010	0.007	0.033	...
borg_1059+0519	1806.0	2.1	164.703900	5.312500	247.014633	55.439033	26.2	26.3	26.8	0.028	0.027	0.020	0.014	0.070	...
borg_1118-1858	6276.0	2.0	169.410100	−18.972600	274.146911	38.600114	26.2	26.3	27.2	0.050	0.048	0.036	0.026	0.124	...
borg_1358+4334	3812.0	2.7	209.463600	43.561000	88.017132	68.790121	26.2	26.3	27.3	0.007	0.006	0.005	0.003	0.016	...
borg_1459+7146	2812.0	2.8	224.750100	71.763800	110.071478	42.032640	26.2	26.3	27.0	0.027	0.026	0.019	0.014	0.067	...
borg_1510+1115	9529.0	1.8	227.537100	11.241500	13.735263	53.779237	26.2	26.3	27.7	0.046	0.045	0.033	0.024	0.115	...
borg_2132-1202	1809.0	1.2	322.946700	−12.039700	40.659355	−40.966360	26.2	26.3	26.2	0.062	0.060	0.045	0.032	0.153	...
borg_2313-2243	6326.0	3.3	348.232600	−22.725200	38.654403	−67.276574	26.2	26.3	27.1	0.026	0.025	0.019	0.013	0.065	...

Table 4
The M-dwarfs Identified by PEARS in the CANDELS Field

ID	Type	R.A.	Decl.	m_{F435W}	m_{F606W}	m_{F775W}	m_{F850W}	m_{F125W}	m_{F160W}
48173	4.0	53.220073	-27.854046	25.22	24.96	23.73	23.15	22.61	22.63
53237	4.0	53.194890	-27.848121	25.19	25.45	24.14	23.49	22.93	22.88
58796	1.5	53.173782	-27.841699	25.70	25.04	24.17	23.85	23.36	23.29
58826	4.3	53.189870	-27.841487	24.76	24.34	23.04	22.39	21.98	21.82
63079	1.0	53.181657	-27.836074	25.49	24.44	23.76	23.47	22.99	23.00
63028	3.7	53.213644	-27.835281	24.29	23.97	22.78	22.15	21.58	21.59
63752	3.9	53.189345	-27.834509	23.80	23.43	22.37	21.74	21.16	21.12
63993	2.0	53.170843	-27.833788	23.81	23.13	22.27	21.91	21.56	21.46
66572	8.4	53.191395	-27.830774	24.60	26.71	24.80	23.58	22.47	22.53
69522	6.0	53.183514	-27.826627	24.89	24.60	23.41	22.64	22.02	21.91
70032	3.9	53.169502	-27.825087	22.88	22.52	21.40	20.77	20.34	20.25
74670	1.0	53.181116	-27.817942	25.79	24.96	24.20	23.97	23.44	23.31
74928	4.0	53.192508	-27.815594	20.55	20.06	19.10	18.51	17.93	17.92
79699	4.0	53.210190	-27.808231	22.75	22.38	21.29	20.66	20.08	20.02
80618	2.0	53.181804	-27.808089	26.31	25.72	24.88	24.48	24.08	24.06
82885	0.2	53.208736	-27.804499	25.77	24.76	24.13	23.83	23.57	23.45
91263	0.9	53.171308	-27.793465	24.35	23.43	22.76	22.49	22.27	22.09
92395	2.1	53.193512	-27.792703	24.44	23.83	22.93	22.54	22.06	22.08
93532	2.0	53.208197	-27.791671	26.19	25.55	24.52	24.07	23.52	23.50
93841	4.9	53.182786	-27.791200	25.10	25.14	23.97	23.34	22.71	22.74
94206	4.3	53.163637	-27.790605	24.71	24.21	23.00	22.37	22.04	21.75
95752	3.8	53.193173	-27.788834	23.42	23.24	22.12	21.53	20.93	20.93
104030	0.0	53.158515	-27.777252	22.95	21.97	21.34	21.16	20.87	20.69
104673	0.0	53.158184	-27.773143	19.76	18.90	18.48	18.04	17.69	17.48

Notes. The optical magnitudes are from Pirzkal et al. (2009) and the $F125W$ and $F160W$ magnitudes from our SEXTRACTOR catalog of the CANDELS field.

50 arcmin² of new data (13 fields) and deeper observations of two previous BoRG pointings. This brings the total J -band area of the BoRG survey to ~ 350 arcmin² and makes BoRG the largest existing near-infrared survey with *HST*, e.g., compared with CANDELS/Wide (260 arcmin²) or Deep (120 arcmin²). We include nine BoRG13 fields as additional lines of sight in our sample (see Table 3).

3. CATALOG GENERATION

To construct the catalogs for the BoRG Fields, we ran SEXTRACTOR (Bertin & Arnouts 1996; Holwerda 2005) with similar settings as Trenti et al. (2011) but set to include MU_MAX, r_{50} , and other morphological information. Source detection was done in the $F125W$ image, with the other filters run in dual-image mode. The multidrizzle weight files were used as rms maps (once normalized, following the prescription in Casertano et al. 2000, WEIGHT_TYPE=MAP_RMS), but scaled appropriately to reflect the noise correlation introduced. The photometric zero-points are from Dressel et al. (2010); Windhorst et al. (2011): $F606W$: 26.08, $F600LP$: 25.85, $F098W$: 25.68, $F125W$: 26.25, and $F160W$: 25.96, respectively, with A_V corrections derived for each individual field (Table 3). These settings resulted in 93106 objects in the BoRG survey.

4. CANDELS AND ERS CALIBRATION CATALOGS

We generated SEXTRACTOR v2.8 catalogs with the same settings as above for the section of the resampled CANDELS mosaic, which includes the PEARS-S coverage (Figure 1) to obtain $F125W$ and $F160W$ luminosities and morphological information for the spectroscopically identified M-dwarfs. Optical magnitudes for these are from ACS photometry presented in Pirzkal et al. (2009). The overlap between the PEARS-S survey and

CANDELS mosaic is a sample of 24 M-dwarfs (Table 4). We will use their morphology to select bona fide stars in the $F125W$ images and their colors to select and subtype the M-dwarfs.

A second calibration catalog of 22 bona fide PEARS-identified M-dwarfs is constructed based on the ERS mosaics (Table 5). The ERS mosaic pixel scale was set to be identical to the BoRG fields, and all of the SEXTRACTOR parameters are kept identical to the BoRG ones. Similar to the CANDELS and BoRG catalog, detection was done in $F125W$ with the catalogs in $F160W$, $F098M$, and $F606W$ or $F600LP$ in dual mode for the respective photometry. Cross-correlation with the PEARS-identified sources used the published right ascension and declination from Pirzkal et al. (2009) converted to pixels, but due to some lingering issues with the WCS coordinates in the ERS data, we are less certain about the cross-identification than in the CANDELS data ($\sim 0''.1$ uncertainty in position). Because of these issues and the uncertainty in the flux calibration between CANDELS and the ERS mosaics (Figure 4), we adopt the CANDELS mosaic as our primary calibrator for morphological selection and subtyping and the ERS to calibrate the color-color selection and as a check of the CANDELS data.

4.1. CANDELS and ERS Photometry

We used the same zero-points for all of the filters as those used for the BoRG survey (Trenti et al. 2011; Bradley et al. 2012) and ERS (Windhorst et al. 2011). However, the ERS data was taken when the WFC3 instrument was still cooling down, and hence one could expect slightly different WFC3 performance between the CANDELS and ERS photometry catalog. To check, we identified stars (using the r_{50} criterion below) in the full ERS mosaic and cross-correlated these with the full CANDELS catalog (derived from the $0''.06$ mosaic). The overlap is 13 point sources. Figure 4 shows the difference SEXTRACTOR magnitudes

Figure 4. Difference in magnitude between the CANDELS and ERS mosaics. The CANDELS *SEXTRACTOR* catalog was generated from the $0''.06$ pixel scale, full mosaic. Cross-correlation with the ERS mosaic yielded 13 stellar objects. There is an offset in both filters between the mosaics.

(A color version of this figure is available in the online journal.)

Table 5
The M-dwarfs Identified by PEARS in the ERS Mosaic

ID	Type	R.A.	Decl.	m_{F435W}	m_{F606W}	m_{F775W}	m_{F850W}	m_{F125W}	m_{F160W}
108497	1.7	53.093027	-27.735838	21.39	20.58	19.78	19.42	19.19	19.07
108014	2.0	53.057966	-27.735053	19.76	18.81	18.37	17.80	17.64	17.47
110839	2.0	53.089621	-27.733082	23.02	22.36	21.48	21.06	21.52	21.30
111269	3.0	53.113985	-27.732740	24.68	23.98	23.05	22.58	21.99	22.05
111982	6.0	53.107958	-27.728253	21.63	21.19	19.94	19.11	18.51	18.41
114688	0.0	53.086462	-27.724381	24.06	23.11	22.49	22.22	22.73	22.41
115223	4.0	53.105121	-27.724124	25.11	24.64	23.51	22.90	22.16	22.18
114563	6.0	53.069511	-27.723391	22.27	21.88	20.69	19.90	19.37	19.12
116612	4.0	53.134575	-27.721317	24.55	23.85	22.70	22.24	21.63	21.53
117391	1.3	53.087638	-27.719656	23.01	22.13	21.42	21.04	20.66	20.67
119050	2.7	53.087816	-27.717329	26.03	24.77	23.84	23.42	23.02	22.81
120814	4.2	53.111938	-27.713369	24.19	23.99	22.87	22.19	21.70	21.61
123686	5.3	53.090399	-27.706629	23.60	23.44	22.25	21.52	20.79	20.72
124539	8.7	53.076943	-27.706018	25.28	25.75	24.27	23.22	22.64	22.52
124624	1.0	53.104778	-27.705292	23.78	23.41	22.76	22.42	21.25	21.08
125478	9.0	53.100622	-27.703149	24.03	24.37	22.53	21.29	20.38	20.34
126754	1.0	53.049225	-27.701327	24.91	23.94	23.19	22.88	22.32	22.21
128173	3.3	53.069739	-27.697205	23.69	23.12	22.11	21.57	21.11	21.09
128247	2.0	53.096541	-27.694200	21.16	20.43	19.62	19.24	18.92	18.78
130804	1.0	53.060606	-27.691367	24.23	23.33	22.66	22.35	21.82	21.71
132690	3.0	53.066145	-27.687565	24.21	23.86	22.91	22.44	21.13	20.77
132690	3.0	53.065896	-27.687864	24.21	23.86	22.91	22.44	22.15	22.29

Notes. The optical magnitudes are from Pirzkal et al. (2009) and the *F125W* and *F160W* magnitudes from our *SEXTRACTOR* catalog of the ERS mosaic.

Table 6

The Difference and rms between the CANDELS and ERS Magnitudes for the *F125W* and *F160W* Filters

Filter	MAG_ISO	MAG_AUTO	MAG_APER
<i>F125W</i>	-0.34 (0.23)	-0.40 (0.26)	-0.43 (0.19)
<i>F160W</i>	-0.26 (0.11)	-0.28 (0.10)	-0.39 (0.10)

Notes. The aperture for MAG_APER is $0''.48$ (8–6 pixels, respectively).

for these stars between the CANDELS and ERS mosaics in the *F125W* and *F160W* filters.

Discarding the faintest objects as their stellarity becomes uncertain (Figure 5), the mean difference between the overlap stars for different apertures ($m_{F125W} < 24$, $m_{F160W} < 23.5$) are listed in Table 6. We take the differences in the MAG_APER as the most reliable because these were computed for identical-size

apertures. Because we used the ASSOC option in *SEXTRACTOR*, the placement of these apertures could conceivably be slightly different (typically less than a pixel difference), but this is not enough to explain the offset in photometry.

Thus, for the following, we correct the ERS photometry by subtracting 0.43 and 0.39 for the *F125W* and *F160W*, respectively. However, we lack similar information for the *F098M* filter and adopt a correction of 0.4 mag, the mean of the correction for the *F125W* and *F160W* corrections.

4.2. Morphological Identification of Stars

To identify the low-mass dwarfs in our catalogs, we opt for a strict morphological selection to allow the color information to be used for identification of the stellar type and subtype. There are several *SEXTRACTOR* parameter cuts in use to identify unresolved sources, all of them a variation on a concentration

Figure 5. Relation between MAG_AUTO and half-light radius (r_{50}) for the common objects between the CANDELS v0.5 field and the ERS (see Figure 1). The green lines are the stellarity criterion for the half-light radius. Beyond $MAG_AUTO \sim 24$, the stellarity of these objects is doubtful.

(A color version of this figure is available in the online journal.)

index; the `CLASS_STAR`, native to `SEXTRACTOR`, the half-light or effective radius (r_{50}) used by Ryan et al. (2011), the flux ratio between to predefined apertures, e.g., the stellarity index $S_2 = MAG_{aper(1\text{ pix})}/MAG_{ISO}(F125W)$ in Pirzkal et al. (2009), and the relation between the brightest pixel surface brightness and total source luminosity (MU_MAX/MAG_AUTO ; Holwerda 2005; Holwerda et al. 2005; Leauthaud et al. 2007, who used it to discard stars).

Using the M-dwarf catalog for CANDELS, we define three morphological criteria: one based on the stellarity index (S_2), one on the MU_MAX/MAG_AUTO ratio, and one for the half-light radius (r_{50}) for the *F125W* catalog. If we fit the relation between S_2 , MU_MAX/MAG_AUTO , and r_{50} with MAG_AUTO for these M-dwarfs we get

$$|S_2 + 0.0065 \times MAG_AUTO - 1.18| < 0.016(0.018), \quad (1)$$

the relation between MU_MAX and the luminosity (MAG_AUTO),

$$\left| \frac{MU_MAX}{MAG_AUTO} - 0.0085 \times MAG_AUTO - 0.65 \right| < 0.019 \quad (2)$$

and the half-light radius (r_{50}),

$$|r_{50} - 0.014 \times MAG_AUTO - 2.03| < 0.23, \quad (3)$$

with the variance in the relation determined from the scatter of the M-dwarfs around the fit. Thus, by definition these criteria will typically select all 24 M-dwarfs in the CANDELS field. Figures 6, 7, and 8 show these three criteria for objects in the CANDELS subfield catalog with the PEARS M-dwarfs highlighted. For comparison, the ERS M-dwarfs are also marked. Table 7 shows how many stars they select in the CANDELS field.

Our goal is to define criteria that would successfully select the PEARS stars. We note that our calibrators are the confirmed M-dwarfs and that some of those objects selected as stars in the CANDELS field are still Galactic stars, just not M-dwarfs. All three criteria work remarkably better than `CLASS_STAR`, selecting stars with little contamination for objects brighter than

Figure 6. S_2 parameter for the CANDELS subfield of Figure 1 (crosses) and the bona fide M-dwarfs identified in this field by PEARS (red points). The green dashed lines indicate our S_2 selection criterion.

(A color version of this figure is available in the online journal.)

Figure 7. MU_MAX/MAG_AUTO parameter for the CANDELS subfield of Figure 1 (crosses) and the bona fide M-dwarfs identified in this field by PEARS (red circles). The green dashed lines indicate our MU_MAX/MAG_AUTO selection criterion.

(A color version of this figure is available in the online journal.)

Table 7

The Number of Selected Objects in the CANDELS/GOODS-S Mosaic Section (Figure 1) for the Three Different Criteria Separately and in Combinations

Criterion	CANDELS <25.5	PEARS M-dwarfs
S_2	216	24
MU_MAX/MAG_AUTO	331	23
r_{50}	120	23

Notes. The mosaic contains 24 bona fide M-dwarfs and we note their selected number as well. Stricter limits resulted in some of those not being selected.

$m_{F125W} < 24$ (Figures 6–9). However, there is a marked difference in efficiency between the S_2 and MU_MAX/MAG_AUTO criteria and the r_{50} criterion in the 24–25.5 mag range. The half-light radius criterion is much stricter than the other two (Table 7), i.e., it includes most of the PEARS-identified M-dwarfs but

Figure 8. r_{50} parameter (half-light radius) for the CANDELS subfield of Figure 1 (crosses) and the bona fide M-dwarfs identified in this field by PEARS (circles). The green dashed lines indicate our r_{50} selection criterion. (A color version of this figure is available in the online journal.)

Figure 9. CLASS_STAR parameter from SEXTRACTOR for the CANDELS subfield of Figure 1 (crosses) and the bona fide M-dwarfs identified in this field by PEARS (circles).

(A color version of this figure is available in the online journal.)

includes much fewer objects from CANDELS than the other two criteria.

The half-light parameter was used by Ryan et al. (2011) in some of these fields to select faint dwarf stars ($1.2 \text{ pixels} \leq r_{50} \leq 1.8 \text{ pixels}$ with their pixel scale set to $0''.09$). Our calibration here shows that this selection criterion is even a little lenient (the selection range can even be narrower), allowing for the different pixel scales, but works very well for the M-dwarfs in these fields.

4.2.1. ERS Catalog Check

The 22 M-dwarfs in the ERS catalog are also plotted in Figures 6–9 to serve as a check for the morphological selection. Their positions in these figures reveal a sensitivity in both the S_2 and the MU_MAX-MAG_AUTO relations for unresolved objects to the pixel scale. The r_{50} criterion is less sensitive to the scale of the pixels. Most likely, this is because it is computed from the growth curve of an object, i.e., the ordered list of pixels.

Figure 10. Relation between the $F606W - F125W$ and $F125W - F160W$ colors for the M-dwarf subtype (0–8) determined from the GOODS, CANDELS, and ERS data for the PEARS spectroscopically identified M-dwarfs.

(A color version of this figure is available in the online journal.)

The other two criteria both depend on an aperture of a single pixel and hence are more sensitive to the pixel scale. Several of the identified objects in the ERS catalog are well away ($r_{50} > 2$ pixels) from those values expected for stars, i.e., unresolved objects. These are likely either misidentifications in the ERS field or blends with other objects or artifacts.

The comparison shows that both the r_{50} and the MU_MAX/MAG_AUTO work well for stellar selection brighter than 24 mag, and the r_{50} includes much fewer interlopers down to 25.5 mag. The practical limit of 24 mag for PEARS-identified M-dwarfs in $F124W$ would limit identifications to distances from 3.2 to 36.3 kpc depending on M-dwarf subtype (M9–M0 respectively), or some 10–100 thin disk scale-heights. We treat our sample as uncontaminated, photometrically accurate, and calibrated with the CANDELS M-dwarfs up to this conservative limit, which is still two magnitudes above the BoRG photometric detection limit (Figure 3).

4.3. M-dwarf Near-infrared Color–Color Selection

The second part of the calibration is an empirical color–color selection for the M-dwarfs in the GOODS-S field. We base the M-dwarf selection in near-infrared (NIR) colors because of the wide range in optical–near-infrared colors M-dwarf subtypes can display (Figure 10). To identify M-dwarfs, we require their $J_{F125W} - H_{F160W}$ and $Y_{F098M} - J_{F125W}$ color to be similar to the distribution of the PEARS-identified M-dwarfs. To find the $J - H$ color range, we can use both of the CANDELS as the ERS catalog, but for the $Y - J$ color we must rely on the ERS catalog alone.

Figure 11 shows the distribution of $J_{F125W} - H_{F160W}$ color for the PEARS M-dwarfs in the CANDELS and ERS fields. These are not in the range one would infer from Ryan et al. (2011) in their Figures 3 and 4, but wider by a few tenths of magnitudes. The ERS and CANDELS $J - H$ colors are still different by ~ 0.1 mag (Figure 11). We suspect that the PEARS M-dwarf $F125W - F160W$ color distribution in CANDELS in Figure 11 is different than the distribution in Ryan et al. (2011) because their colors were derived from spectra convolved with appropriate filter response functions. There is however an

Figure 11. Histogram of the $F125W - F160W$ colors from CANDELS and ERS of the PEARS spectroscopically identified M-dwarfs.

(A color version of this figure is available in the online journal.)

Figure 12. Plot of the $F125W - F160W$ and $F098M - F125W$ colors from the ERS of the 22 PEARS spectroscopically identified M-dwarfs.

(A color version of this figure is available in the online journal.)

underreported drop in WFC3 detector sensitivity on the red side of the $F160W$ filter (M. Andersen et al., in preparation; M. Andersen et al. 2011, private communication). The $F098M$ and $F125W$ filters, however, do not suffer from the detector sensitivity degradation at the red side. This could in part account for the small difference in $J - H$ color of the CANDELS M-dwarfs, whose photometry we trust, with the position of M-dwarfs in Figure 3 in Ryan et al. (2011) or the difference in $F125W - F160W$ color with the ERS as the detector was still cooling down (Figure 11).

The ERS mosaics are in the same NIR filters as the BoRG fields ($F125W$, $F160W$, and $F098M$), and Figure 12 shows the position of the 22 objects matched to PEARS M-dwarfs in a $J - H$, $Y - J$ color-color plot. We show the same color criteria as Figures 3 and 4 in Ryan et al. (2011). The width and position of the $Y - J$ color criterion is close to what one would infer from Figure 3 in Ryan et al. (2011).

Figure 13. Relation between $sdss - r - J$ color and spectral type from Hawley et al. (2002). M-dwarfs are 0–1 with subtype as the decimal, L-dwarfs are 1–2 with the subtypes as the decimal, and T-dwarfs are type 3 with the decimal the assigned subtype because molecular lines start to dominate the spectrum. The later type dwarfs do not show a good linear relation between a wide optical–near-infrared color and subtype. However, they do show a redder color than all of the M-dwarf subtypes, and hence we can exclude almost all substellar objects based on color.

Based on both Figures 11 and 12, we define a near-infrared color–color criterion to select M-dwarfs in the BoRG survey; $-0.05 < J - H < 0.3$ and $0.1 < G - J < 0.75$ (the solid blue boxes in Figures 12 and 19 in addition to the L, T, and MLT boxes from Ryan et al. (2011)).

4.4. Subtyping M-dwarfs

Our last calibration involving the PEARS-identified M-dwarfs in the CANDELS and ERS mosaics of the GOODS-S field is to derive a color-subtype relation. Figure 13 shows the relation between $r - J$ color and dwarf type from Hawley et al. (2002). M-dwarfs show a linear relation with a color provided the baseline is long enough, i.e., optical to infrared. The later L- and T-dwarfs do not have such a clear relation.

Figure 14 shows the relation between the $V_{F606W} - J_{F125W}$ color and the spectroscopic subtype as determined by Pirzkal et al. (2009) for the 24 PEARS M-dwarfs in CANDELS and the 22 PEARS M-dwarfs in the ERS. They obtain a type from template fits to each ACS grism spectrum obtained for these objects. Because of the design of the PEARS observations, there are often several spectra taken at different roll angles. Cross-comparison between the spectral fits show that the uncertainty in the PEARS type classification is less than an M-dwarf subtype. We therefore take these spectral types as our gold standard for the classification of the stellar objects in the WFC3 parallel fields.

Figure 14 shows the relation between the $V - J$ color and spectroscopic type from PEARS. We fit a linear relation to the CANDELS sample because it is the cleanest selection and photometry. The linear relation in the PEARS-identified CANDELS M-dwarfs can be expressed as

$$M_{\text{type}} = 3.39 \times [V_{F606W} - J_{F125W}] - 3.78. \quad (4)$$

The M-dwarfs identified by PEARS in the ERS mosaic display more scatter than the CANDELS M-dwarfs, but after correction of the $F125W$ magnitudes (see above), the $V - J$ colors and their PEARS subtype generally agree well with the

Figure 14. Relation between M-dwarf subtype (0–8) and the $F606W-F125W$ color relation as determined from the GOODS, CANDELS, and ERS data for the PEARS spectroscopically identified M-dwarfs. There is a linear relation between this color and the subtype that we use to type the dwarfs in the BoRG WFC3 parallel fields. We show three fits: one based on all M-dwarfs ($t < 6$), only the CANDELS M-dwarfs ($t < 6$), and only the ERS M-dwarfs. We adopt the CANDELS relation because this sample is the cleanest with accurate photometry and exposure times similar to the BoRG fields.

(A color version of this figure is available in the online journal.)

Figure 15. Residual between $V - J$ inferred subtype and the spectroscopic subtype from PEARS for the M-dwarfs in the ERS and CANDELS data. The ERS $F125W$ photometry may be shifted slightly still with respect to the CANDELS (Figure 11), and this may account for the higher scatter for this subset.

(A color version of this figure is available in the online journal.)

relation derived from the CANDELS M-dwarfs, although some difference may remain (Figure 11).

Figure 15 shows the residual between the $V - J$ color type and PEARS spectroscopic type. The PEARS M-dwarfs cover mostly subtype 0–5 and only a few M ($t > 6$) are in this sample. Consequently, the color-subtype relation is most reliable for the earlier subtypes. Based on Figure 15, we take that our subtype based on $V - J$ color is accurate within a subtype. We adopt this relation to type M-dwarfs in the BoRG fields and compute type uncertainties as a result of the photometric uncertainty in the $F606W$ and $F125W$ magnitudes. We use the absolute

Figure 16. Histogram of the difference in $F600W$ and $F600LP$ MAGAUTO values for those stars in the M-dwarf near-infrared criteria for the three fields in the BoRG survey that have data in both filters.

Table 8
Absolute Two Micron All Sky Survey J -band ($F125W$) Magnitudes of M-dwarfs from Hawley et al. (2002)

Subtype	M_J
0	6.45
1	6.72
2	6.98
3	7.24
4	8.34
5	9.44
6	10.18
7	10.92
8	11.14
9	11.43
10	11.43

magnitudes from Hawley et al. (2002) to compute distance moduli (Table 8) and infer distances.

4.5. Substituting $F600LP$ for $F606W$ Photometry

In the case of 24 fields in the BoRG survey, $F606W$ photometry is not available. These fields come from the HIPPIES or COS-GTO parallel observations, which opted for $F600LP$ rather than $F606W$. The $F600LP$ filter has a slightly different width compared to the $F606W$ and a different central wavelength (closer to Johnson- I). Fortunately, there are three fields for which both $F606W$ and $F600LP$ data are available. We compared the $F606W - F600LP$ colors for those objects already preselected by their near-infrared color and morphology as likely M-dwarfs to assess the impact of the change of filters. Figure 16 shows the histogram of the color difference between the two bandpasses for M-dwarfs. The difference is substantial: $F600LP - F606W = -2.65$ mag with a spread of 0.88 mag. Therefore we correct our $F600LP$ photometry with this difference and increase the uncertainty in the photometry accordingly as well (which should be reflected in the subsequent automated typing).

5. STARS IN THE BoRG WFC3 PURE-PARALLEL FIELDS

With the morphological and near-infrared color-color selection in hand, we now search the BoRG fields for M-dwarfs as

Figure 17. $F125W$ half-light radius as a function of magnitude for all of the BoRG fields. The green dashed lines are the selection criteria from Equation (3) to identify stars in these fields. Objects below the bottom green line are more likely to be defects (e.g., remaining hot pixels).

(A color version of this figure is available in the online journal.)

well as other substellar types. Figure 17 shows the same parameter space as Figure 8 but with all of the BoRG objects. Based on the r_{50} selection criterion, we find 1308 stars to 24 mag in $F125W$ in the 59 WFC3 parallel fields. For comparison, Figure 18 shows the other morphology criteria. The r_{50} selection criterion seems the most appropriate for the BoRG fields because the locus of stellar points is within the criterion lines. S_2 appears equally applicable, but the MU_MAX/MAG_AUTO criterion shows a discrepancy compared to Figure 7. We suspect this is because the CANDELS data was originally at a different pixel size, and this criterion is sensitive to the exact pixel scale of the image. Figure 17 validates therefore our adoption of the r_{50} criterion for the morphological selection of stars.

To identify the various subtypes of stars, we construct an NIR color-color diagram similar to Figure 3 in Ryan et al. (2011), as discussed above. Figure 19 shows this plot with the limits for our selection criteria for approximate types. In the BoRG *SEXTRACTOR* catalog, we identify 30 L-dwarfs, 1 T-dwarfs, 274 M-dwarfs, and 29 M-, L-, or T-dwarfs based on the color cuts. The M-dwarf sample is the one of interest here.

Figure 19. $J_{F125W} - H_{F160W}$ vs. $G_{F098M} - J_{F125W}$ color diagram, similar to Figure 4 from Ryan et al. (2011), to distinguish between L-, T-, and M-dwarfs. (A color version of this figure is available in the online journal.)

Tables 14, 15, and 16 list the properties of the identified stars that conform to the M-, T-, and L-dwarf color cuts (Figure 19).

Subsequently, we subtype the M-dwarfs according to Equation (4). Figure 20 shows the histogram of M-dwarf subtypes in the BoRG fields as well as those objects in the MLT box in Figure 19 for comparison. In effect this is an additional optical-near-infrared color criterion for M-dwarf selection because we will discard any star that could not be subtyped. The dominant type in our M-dwarf sample is M0, specifically -1 to 1 type, not unexpectedly because these are the brightest and most numerous type of M-dwarf. There are almost as many later-type M-dwarfs (M4 and above) in the MLT color selection as in our exclusively M-dwarf box. However, as we note above, the later type classification is the most uncertain and in the MLT box susceptible to L- and T-dwarf contamination.

There is still the possibility of contamination by giants, subdwarfs, and AGNs, but we are confident that the morphological selection, luminosity limit, and the color-color restriction select a very clean sample of Milky Way M-dwarfs.

5.1. Contamination by M-giants or M-type Subdwarfs

Bochanski et al. (2014) present a catalog of 404 M-giants from the UKIDSS survey DR8 (2400 deg², $K < 17$), with

Figure 18. Two alternative morphological selections for stars for the BoRG data: the S_2 and the μ_{max}/mag_auto ratio.

(A color version of this figure is available in the online journal.)

Figure 20. Histogram of M-dwarf types in our BoRG, inferred from Equation (4). M0 and M1 are the most prevalent in the sample. As can be seen in the histogram, some of the stellar objects are not M-dwarfs but either other substellar objects or possibly very distant (intergalactic?) M-giants.

(A color version of this figure is available in the online journal.)

these M-giants among the most distant stars belonging to the Milky Way. In principle, M-giants could be selected by our color selection. However, their on-sky density (4.3×10^{-5} M-giants/arcmin²) makes it unlikely not impossible that even a single one is included in our selection. One could make a similar plausibility argument against very nearby M-type subdwarfs: the volume probed at close distances is comparatively small for a pencil beam survey.

6. DISCUSSION

Based on our *bona fide*, morphological- and color-selected M-dwarfs and the subsequent color subtyping, we explore the north–south discrepancy, the Galactic thin disk scale-height as a function of subtype, and whether or not we detect any additional Galactic component (halo or thick disk).

6.1. The North–South Divide

Pirzkal et al. (2009) found a north–south discrepancy between the number of M-dwarfs in the PEARs fields. They find 51 and 63 M0–9 dwarfs in the GOODS north and south fields, respectively. Accounting for the different field sizes (41.61 arcmin² and 59.50 arcmin², respectively), this is equivalent to 1.23 and 1.06 M-dwarfs arcmin^{−2}, an excess of 11% in the northern field. Both GOODS fields are at similar Galactic latitude, and Pirzkal et al. note that because the Sun is north of the Galactic plane, the northern excess appears to be a contradiction. Widrow et al. (2012) and Yanny & Gardner (2013) find similar north–south discrepancies in the Sloan Digital Sky Survey (SDSS) catalog of (dwarf) stars in the solar neighborhood.

One of our science goals with this study was to establish if this is a real discrepancy due to natural field variance. The BoRG fields are over many more lines of sight and a division of these in Galactic northern and southern fields result in 134.5 and 72.1 arcmin², respectively. We count the M-dwarfs in those fields above 20° Galactic longitude to avoid two southern fields that sample more along the Galactic plane.

We find on average 1.157 ± 0.088 M-dwarfs of all types (M0–9) per arcmin² in the northern fields and $1.293 \pm$

Figure 21. Distribution of BoRG fields with the number of M-dwarfs indicated. One field, borg_1230+0750 (star) stands out with 22 M-dwarfs (~ 20 stars arcmin^{−2}). We discard borg_1815-3244 (black circle) for its low latitudes and line of sight through the plane of the disk and close to the center of the bulge.

(A color version of this figure is available in the online journal.)

Table 9
Average Number of M-dwarfs per Square Arcminute in Southern and Northern Galactic Fields ($|l| > 20^\circ$)

	M-dwarfs North	South	North /South	S/N
M-dwarfs	1.157 ± 0.088	1.293 ± 0.127	0.89	8.02
M0-4	0.859 ± 0.076	0.779 ± 0.099	1.10	6.45
M5-10	0.210 ± 0.038	0.465 ± 0.076	0.45	4.11
M0	0.304 ± 0.045	0.176 ± 0.047	1.73	3.27
M1	0.156 ± 0.032	0.151 ± 0.043	1.03	2.81
M2	0.115 ± 0.028	0.088 ± 0.033	1.31	2.23
M3	0.088 ± 0.024	0.075 ± 0.031	1.17	2.03
M4	0.196 ± 0.036	0.289 ± 0.060	0.68	3.58
M5	0.095 ± 0.025	0.364 ± 0.068	0.26	3.07
M6	0.007 ± 0.007	0.025 ± 0.018	0.27	0.82
M7	0.041 ± 0.017	0.025 ± 0.018	1.62	1.22
M8	0.041 ± 0.017	0.013 ± 0.013	3.23	0.93
M9	0.020 ± 0.012	0.038 ± 0.022	0.54	1.22
M10	0.007 ± 0.007	0.000 ± 0.000	0.00	0.00

Notes. M-dwarf numbers refer to those objects in the blue box in Figure 19. The last two columns are ratio of M-dwarfs in northern and southern fields and the signal-to-noise ratio.

0.127 arcmin^{−2} in the southern Galactic fields (Table 9), which agrees with the previously observed discrepancy. The northern overdensity is the most pronounced in the early (M0–4) type M-dwarfs. Taking into consideration that for these early types the statistics are more secure, and early types dominate the grism sample of Pirzkal et al. (2009) (or the SDSS catalog); our counts corroborate the previously found north–south discrepancy. The northern overdensity is most pronounced in the earliest types, gradually diminishing and reversing for late-type M-dwarfs (Table 9).

6.2. A Local Overdensity of M-dwarfs

A single field, borg_1230+0750, stands out from the other BoRG fields with a local density of 21.4 M-dwarfs arcmin^{−2}.

Figure 22. Distribution of M-dwarf distances in borg_1230+0750, with a concentration at 20–25 kpc.

Such overdensities of faint Galactic stars are a possible contaminant for identifications of overdensities of high-redshift clusters (e.g., Trenti et al. 2012).

The Galactic position of this overdensity ($l = 287^\circ 119670593$, $b = 70^\circ 0322203957$, Figure 21) argues against a spiral arm or disk substructure as the origin of this overdensity. However, its position is exactly on the Sagittarius stellar stream (Majewski et al. 2003; Belokurov et al. 2006). Figure 22 shows the histogram of photometric inferred distances for the M-dwarfs in borg_1230+0750. The distance of the overdensity of M-dwarfs at 20–25 kpc is also in line with these M-dwarfs belonging to the Sagittarius stream (Newberg et al. 2002; Belokurov et al. 2014) at this Galactic longitude.

The relative ease with which this stellar stream was identified in the BoRG data shows that the future *EUCLID* mission will identify virtually *all* streams in the Milky Way halo from the dwarf stars alone.

6.3. Thin Disk Scale-Height

Previous studies based on small numbers of fields have already given us several estimates of the scale-height of the thin disk of the Milky Way in substellar objects (Table 1). The consensus appears to be a scale-height between 300 and 400 pc for the thin disk. For M-dwarfs, Jurić et al. (2008) find a thin disk of $z_0 = 300$ pc and a thick disk with $z_0 = 900$ pc from SDSS data.

To estimate the distances to each M-dwarf, we compute the distance modulus from the inferred subtype (and hence absolute magnitude) and the apparent magnitude in *F125W*. We compute the Galactic radius and height above the plane for all M-dwarfs, based on their Galactic longitude, latitude, and the above distance, assuming the position of the Sun is 27 pc above the plane and at a Galactocentric radius of 8.5 kpc from the Galactic center. To compute the density at each M-dwarf’s position, we compute the physical area at the inferred distance of the BoRG survey field in which the dwarf was found and a bin-width of 1 pc.

We discard one field (borg_1815-3244) for two reasons: it is at low Galactic latitude with a line of sight straight through the Galactic bulge (Figure 21), and there is only *F600LP* information available, which makes subtyping of M-dwarfs

Figure 23. Computed volume for each M-dwarf as a function of Galactocentric radius, height above the plane. M-dwarf types as inferred from their optical–NIR color.

(A color version of this figure is available in the online journal.)

more uncertain. This field contains 67 M-dwarf candidates, but these are not used for the following analysis.

Figure 23 shows the distribution of radius and height above the disk for the 274 stars in the BoRG survey with their corresponding number density and type. The fainter late-subtype M-dwarfs are in a localized thin disk, and the bright early-subtype (e.g., M0) correspond more closely to the thick disk component.

We assume that the Galactic disk has the following parametric shape:

$$\rho(R, z) = \rho_0 \exp(-R/h) \operatorname{sech}^2\left(\frac{z}{z_0}\right), \quad (5)$$

where $\rho(R, z)$ is the dwarf number density in a point in the disk, ρ_0 is the central number density, R is Galactocentric radius, h is the scale-length, z is height above the plane, and z_0 is the scale-height of the disk.

To collapse Figure 23, we weight the volume densities with the exponential part of this equation because we aim to infer the vertical structure first, i.e., we assume a single scale-length and calculate $\exp(-R/h)$ as a weight for each dwarf volume density. In Figure 24, the volume densities have all been scaled this way, assuming the scale-length (h) of the thin disk from Jurić et al. (2008) of 2.6 kpc. They found a scale-length for the thick disk of $h = 2.9$ kpc. Alternatively, Bensby et al. (2011) found a thin-disk scale-length of $h = 3.8$ kpc and $h = 2.0$ for the thick disk, corroborated by Cheng et al. (2012) and the trend of stellar population and scale-length in Bovy et al. (2012). We use the Bensby et al. thin disk scale-length for dwarfs found below 500 pc and the thick disk one for those more than 500 pc out of the plane. The implicit assumption in this renormalization is that the scale-height does not change with radius, which is observed in external galaxies seen edge-on (Comerón et al. 2011a, 2011b, 2011c; D. Streich et al., in preparation).

Figure 24 shows more clearly how the later-type M-dwarfs (M4–8) in the BoRG fields are concentrated in the thin disk and the earlier types (M0–3) probe both thin and thick disks. It also shows that there may be several disk components in early types with different scale-heights above and below the plane of

Figure 24. Volume density of M-dwarfs as a function as height above the plane of the Milky Way disk. The volume densities were normalized with a scale-length of 2.6 kpc. Points are color-coded by the M-dwarf subtype.

(A color version of this figure is available in the online journal.)

Table 10

The Vertical Profile Fits to the Full Sample of Identified M-dwarfs

M-type (°)	ρ_0 (#/pc ³)	z_0 (kpc)
0	4.25	22.85 ± 32.92
1	8.44	15.50 ± 14.33
2	5.29	12.62 ± 9.22
3	373.12	10.69 ± 14.41
4	53.93	-5.17 ± 2.74
5	27.27	2.97 ± 1.39
6	65.78	1.24 ± 0.42
7	14185.51	0.28 ± 0.41
8	1066.36	0.28 ± 0.12

the disk. This would explain the north–south differential noted earlier by Pirzkal et al. (2009).

First we perform a naive fit on the vertical distribution of M-dwarfs as a function of subtype: we fit the $\text{sech}^2(z/z_0)$ to their densities for each subtype, disregarding the different sampling or the existence of more than a single disk component. Fit parameters ρ_0 and z_0 are listed for each M-dwarf type in Table 10. The fit to the M4 dwarfs distribution is not a physical solution. Figure 25 shows the best fits to the densities, and Figures 26 and 27 show the central density and scale-height as a function of type.

The central densities in Figure 26 are not scaled by the central volume density of dwarfs. For comparison, we plot the volume densities computed from the local number of M-dwarfs compiled in Reid et al. (2008), their Figure 7, which is based on the numbers reported in Reid et al. (2004, 2007) and Cruz et al. (2007) for the latest M-dwarf types (M7–10). Table 11 lists the local densities as a function of M-dwarf type. We only note that both stay relatively constant with M-dwarf subtype.

Figure 27 shows the dependence of scale-height, z_0 , with M-dwarf subtype. The progressive decline in scale-height with subtype is in part due to the different heights sampled. Early types are a mix of thin and thick disk, whereas later types were only found in the thin disk.

Bovy et al. (2012) argue that the different metallicity (and hence age) populations of the Milky Way all have their own

Figure 25. Volume density of M-dwarfs as a function as height above the plane of the Milky Way disk. Points are grayscale-coded by the M-dwarf subtype with best fits shown for each M-dwarf type.

(A color version of this figure is available in the online journal.)

Figure 26. Central density of the best fit as a function of the M-dwarf type. The black circles are the values from Reid et al. (2008).

Figure 27. Scale-height of the best fit as a function of the M-dwarf type. Dashed lines are the uncertainty in the fit.

Figure 28. Volume density of M-dwarfs as a function of height above the plane of the Milky Way disk. Points are color-coded by the dwarf’s Galactic longitude (left) and latitude (right panel).

(A color version of this figure is available in the online journal.)

Table 11

Local Dwarf Density from Figure 8 in Reid et al. (2008) and Cruz et al. (2007)

Subtype	Number within 20 pc	
	Reid et al. 2008	Cruz et al. 2007
0	35	
1	50	
2	140	
3	90	
4	350	
5	400	
6	190	
7	170	21
8	45	21
9	60	11
10	42	3

distinct and unique scale-length and scale-height. They find that older populations are more concentrated (shorter scale-length) but the most vertically distributed (greatest scale-height). Similar results were found by Bensby et al. (2011) (using a thin-thick disk terminology) and Cheng et al. (2012). The trend between scale-height and M-dwarf subtype in Figure 27 fits with this general picture that there are not distinct thick and thin disks but a gradual transition in scales with stellar population. Because the majority of our fields are high Galactic latitude, we lack the statistics to perform a double fit (vertical and radial). We note, however, that our use of the Bensby et al. (2011) thick- and thin-disk scale-lengths improved the vertical fits substantially over a single scale-length solution.

There are several “spurs” of stars in the height-density plot of Figure 25. To investigate if these correspond to specific areas in the Milky Way, we replot the height-density plot for all M-dwarfs, coded with the Galactic position in Figure 28. Substructures become visible as a function of Galactic longitude. For example, the upturn in M-dwarfs at 0 to -10 kpc above the plane is due to a few fields near $l \geq 310^\circ$ and $b = -40^\circ$. The longitude position strongly suggests the Milky Way bulge as the origin of the additional M-dwarfs, but the latitude is quite low for much of the effect of the Galactic bulge.

To characterize the different scale-heights implied by the spurs in Figure 28, we selected Galactic longitude or latitude sections for a sech^2 fit, summarized in Tables 12 and 13. The sech^2 fits to these cuts show an expected variety of z_0 values. Given the vertical extent that the observations probe, contributions from stellar halo components are likely included

Table 12

The Fits to Selected Galactic Latitude Cuts

b ($^\circ$)	ρ_0 ($\#/\text{pc}^3$)	z_0 (kpc)
-75.00	140.03	0.77 ± 0.00
-55.00	60.60	2.14 ± 0.07
10.00	451455.50	0.02 ± 0.01
35.00	2394.64	0.19 ± 0.00
52.00	172.83	1.48 ± 0.27
60.00	25.13	1.98 ± 0.01

Table 13

The Fits to Selected Galactic Longitude Cuts

l ($^\circ$)	ρ_0 ($\#/\text{pc}^3$)	z_0 (kpc)
310.00	6.45	6.68 ± 0.38
235.00	716.35	0.28 ± 0.00
75.00	12.64	32.24 ± 77.73
85.00	1921.33	0.54 ± 0.00
120.00	3875.14	0.13 ± 0.01
140.00	12.58	3.84 ± 3.12

(similar to the Sagittarius stream in Section 6.2). For example, the spur of stars at 20 kpc at $l = -75^\circ$ and $b = -75^\circ$ (yellow and red points in Figure 28, left and right panels, respectively) is at a higher density than one would expect from the different latitude observations at $l = 120^\circ$ (green point in Figure 28, left panel). However, that spur is the result of a single field, and this may be simple cosmic variance in our counts. To reliably detect halo substructure or even typical scales using M-dwarfs, one needs to image a much greater area of sky continuously (i.e., with *EUCLID*).

6.4. L-Dwarfs and T-Dwarfs

We do find a number of stellar objects in the L and T color selection criteria from Ryan et al. (2011). There is one object brighter than 24 mag in *F125W* in these fields that fall into the T-dwarf box. This is not the sole T-dwarf identified by Ryan et al. (2011), which is a 25.08 mag object. The color-color selection also identifies 30 L-dwarfs in the BoRG survey. Table 14 lists their properties. Table 15 lists the properties of the single $m < 24$ T-dwarf stars in BoRG. Neither T- nor L-dwarfs have a reasonably well-calibrated relation between optical-near-infrared color and subtype (see, e.g., Burningham et al. 2013)

Table 14
The 30 L-dwarfs Identified in BoRG

ID	R.A.	Decl.	l	b	m_{F098M}	m_{F125W}	m_{F125W}	m_{F606W}
borg_0110-0224.1010.0	17.537240	-2.409470	17.537240	-2.409470	24.7 ± 0.1	23.7 ± 0.0	23.5 ± 0.0	25.3 ± 0.1
borg_0439-5317.882.0	69.836642	-53.263207	69.836642	-53.263207	24.0 ± 0.0	22.7 ± 0.0	22.2 ± 0.0	24.8 ± 0.9
borg_0540-6409.2993.0	84.876906	-64.132531	84.876906	-64.132531	25.0 ± 0.1	23.8 ± 0.0	23.4 ± 0.0	26.8 ± 0.6
borg_0751+2917.567.0	117.684321	29.285619	117.684321	29.285619	19.5 ± 0.0	17.8 ± 0.0	17.6 ± 0.0	19.6 ± 0.0
borg_0808+3946.457.0	122.094091	39.759095	122.094091	39.759095	25.0 ± 0.1	23.9 ± 0.0	23.5 ± 0.0	26.9 ± 0.6
borg_0819+4911.264.0	124.831743	49.175806	124.831743	49.175806	23.9 ± 0.0	22.8 ± 0.0	22.4 ± 0.0	27.9 ± 1.6
borg_0906+0255.462.0	136.409407	2.923645	136.409407	2.923645	24.4 ± 0.0	23.3 ± 0.0	22.8 ± 0.0	27.6 ± 0.8
borg_0909+0002.748.0	137.292821	-0.012257	137.292821	-0.012257	24.5 ± 0.1	23.2 ± 0.0	22.8 ± 0.3	26.6 ± 0.4
borg_0914+2822.673.0	138.558022	28.364206	138.558022	28.364206	24.8 ± 0.1	23.5 ± 0.0	23.1 ± 0.0	26.3 ± 0.3
borg_0926+4426.581.0	141.355847	44.425445	141.355847	44.425445	24.3 ± 0.0	23.1 ± 0.0	22.6 ± 0.0	25.2 ± 0.9
borg_1103-2330.623.0	165.819910	-23.506010	165.819910	-23.506010	23.9 ± 0.1	22.9 ± 0.0	22.5 ± 0.0	25.7 ± 0.2
borg_1111+5545.1125.0	167.747157	55.771759	167.747157	55.771759	23.6 ± 0.0	22.5 ± 0.0	22.1 ± 0.0	26.6 ± 0.3
borg_1153+0056.247.0	178.200215	0.922794	178.200215	0.922794	23.9 ± 0.0	22.9 ± 0.0	22.4 ± 0.0	26.2 ± 0.3
borg_1230+0750.2419.0	187.471709	7.820117	187.471709	7.820117	23.9 ± 0.1	22.8 ± 0.0	22.3 ± 0.0	26.2 ± 0.3
borg_1301+0000.1067.0	195.326828	0.013297	195.326828	0.013297	23.5 ± 0.1	22.2 ± 0.0	21.8 ± 0.0	24.3 ± 0.9
borg_1337+0028.1117.0	204.205278	-0.445870	204.205278	-0.445870	24.3 ± 0.2	23.1 ± 0.0	22.7 ± 0.0	25.3 ± 0.9
borg_1524+0954.24.0	231.044740	9.885957	231.044740	9.885957	24.9 ± 0.1	23.0 ± 0.1	22.8 ± 0.1	25.3 ± 1.0
borg_1632+3733.65.0	248.069017	37.540353	248.069017	37.540353	24.5 ± 0.0	23.3 ± 0.0	22.9 ± 0.0	28.5 ± 2.1
borg_1632+3733.349.0	248.080963	37.550065	248.080963	37.550065	23.5 ± 0.0	22.4 ± 0.0	22.0 ± 0.1	27.1 ± 1.4
borg_1632+3733.1325.0	248.076265	37.572819	248.076265	37.572819	24.3 ± 0.0	23.0 ± 0.1	22.5 ± 0.0	26.7 ± 0.5
borg_2132+1004.284.0	323.058751	10.068991	323.058751	10.068991	16.8 ± 0.0	15.0 ± 0.0	14.7 ± 0.0	17.2 ± 0.9
borg_2132+1004.332.0	323.060235	10.059801	323.060235	10.059801	21.2 ± 0.0	19.9 ± 0.0	19.7 ± 0.0	22.2 ± 0.9
borg_2155-4411.227.0	328.831076	-44.185153	328.831076	-44.185153	23.5 ± 0.0	22.5 ± 0.0	22.2 ± 0.0	24.8 ± 0.9
borg_2155-4411.974.0	328.809893	-44.164189	328.809893	-44.164189	24.3 ± 0.0	23.0 ± 0.0	22.5 ± 0.0	25.1 ± 0.9
borg_2351-4332.1314.0	357.668728	-43.514053	357.668728	-43.514053	25.2 ± 0.1	23.9 ± 0.0	23.5 ± 0.0	26.0 ± 0.9
borg_0456-2203.920.0	73.945566	-22.049396	73.945566	-22.049396	24.6 ± 0.1	23.4 ± 0.0	23.2 ± 0.0	24.4 ± 0.0
borg_1059+0519.644.0	164.717943	5.301323	164.717943	5.301323	24.4 ± 0.0	23.1 ± 0.0	22.6 ± 0.0	26.5 ± 0.3
borg_1118-1858.1915.0	169.392755	-18.972497	169.392755	-18.972497	24.8 ± 0.0	23.8 ± 0.0	23.3 ± 0.0	26.1 ± 0.1
borg_1459+7146.1298.0	224.751450	71.780685	224.751450	71.780685	24.8 ± 0.2	23.5 ± 0.0	23.1 ± 0.0	25.7 ± 0.1
borg_2132-1202.6461.0	322.941469	-12.021619	322.941469	-12.021619	24.6 ± 0.1	23.4 ± 0.0	23.0 ± 0.0	26.5 ± 0.4

Table 15
The 1 T-dwarfs Identified in BoRG

ID	R.A.	Decl.	l	b	m_{F098M}	m_{F125W}	m_{F125W}	m_{F606W}
borg_0540-6409.1929.0	84.862502	-64.152446	84.862502	-64.152446	22.9 ± 0.0	21.9 ± 0.0	22.2 ± 0.0	21.5 ± 0.0

Table 16
The 274 M-dwarfs Identified in BoRG

ID	R.A.	Decl.	l	b	m_{F098M}	m_{F125W}	m_{F160W}	m_{F606W}	Mtype	Modulus	Dist	Height	Radius
borg_0110-0224.551.0	17.501759	-2.418265	17.501759	-2.418265	23.8 ± 0.0	23.5 ± 0.0	23.3 ± 0.0	25.2 ± 0.1	-0.0 ± 0.2	16.48	19.74	-0.81	27.33
borg_0110-0224.719.0	17.503586	-2.415663	17.503586	-2.415663	24.3 ± 0.1	24.0 ± 0.0	23.9 ± 0.0	25.8 ± 0.1	5.1 ± 1.0	16.73	22.16	-0.91	29.63
borg_0110-0224.820.0	17.528020	-2.411389	17.528020	-2.411389	19.7 ± 0.0	19.5 ± 0.0	19.4 ± 0.0	22.8 ± 0.0	0.6 ± 0.2	8.59	0.52	0.01	9.00
borg_0110-0224.1016.0	17.553100	-2.408888	17.553100	-2.408888	24.5 ± 0.1	23.9 ± 0.0	23.7 ± 0.0	25.4 ± 0.1	6.0 ± 0.7	17.18	27.26	-1.12	34.49
borg_0110-0224.1414.0	17.559120	-2.400783	17.559120	-2.400783	24.1 ± 0.1	23.7 ± 0.1	23.4 ± 0.0	24.4 ± 0.1	11.6 ± 0.2	17.26	28.31	-1.16	35.49
borg_0110-0224.1529.0	17.564067	-2.398369	17.564067	-2.398369	24.2 ± 0.1	23.9 ± 0.0	23.8 ± 0.1	25.8 ± 0.2	2.0 ± 0.3	16.67	21.59	-0.88	29.08
borg_0110-0224.2048.0	17.516425	-2.384891	17.516425	-2.384891	22.8 ± 0.0	22.5 ± 0.0	22.2 ± 0.0	24.4 ± 0.0	5.8 ± 0.4	15.23	11.11	-0.44	19.09
borg_0110-0224.2599.0	17.523929	-2.371366	17.523929	-2.371366	22.3 ± 0.0	22.2 ± 0.0	21.9 ± 0.0	23.5 ± 0.0	2.6 ± 0.5	15.46	12.33	-0.48	20.26
borg_0110-0224.2683.0	17.528492	-2.352761	17.528492	-2.352761	24.4 ± 0.1	23.8 ± 0.0	23.5 ± 0.0	26.1 ± 0.2	-0.5 ± 0.3	15.47	12.40	-0.48	20.32
borg_0110-0224.3274.0	17.527112	-2.365442	17.527112	-2.365442	21.5 ± 0.0	21.2 ± 0.0	20.9 ± 0.0	23.0 ± 0.0	7.3 ± 0.0	14.22	6.99	-0.26	15.16

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)

to allow for a distance estimate similar to the M-dwarfs, nor do we have the statistics in hand to infer a scale-height for these objects.

Wilkins et al. (2014) reiterate that L- and T-dwarfs pose a risk of contaminating high-redshift ($z \sim 7$) color-selected samples and show how some dwarf spectra may even masquerade as objects with emission lines. They generated their color selections similar to Ryan et al. (2011), and the boxes in Figure 12 do generally agree with the derived colors. Wilkins et al. (2014) claim *HST* morphological information is insufficient to cull L- and

T-dwarfs from a high-redshift galaxy sample. We have shown that dwarfs can be unequivocally identified by their stellar morphology using simple tools such as *SEXTRACTOR* down to 24 AB mag in *undithered* WFC3 data, and a reliable stargalaxy separation is not only crucial for high-redshift studies but very likely possible down to much lower luminosities. The second issue is the surface density of these later dwarf types. For the first time, we can give an indication for random high-latitude, space-based observations based on the number of L-dwarfs found (Table 14). Figure 29 shows the surface density of L-dwarfs

Figure 29. Distribution of BoRG fields with the number of L-dwarfs indicated. Other symbols identical to Figure 21.

(A color version of this figure is available in the online journal.)

selected by our morphology and color criteria. It shows a WFC3 exposure has <1 L-dwarf that can be selected against morphologically. Extrapolating to lower luminosities (including improved stargalaxy separation), the contamination problem may not be as dire as predicted. For example, Wilkins et al. (2014) assume that the local brown-dwarf density ($0.015 \text{ stars pc}^{-3}$) holds throughout all of the Milky Way components (thin and thick disks and halo). However, the spatial density drops exponentially with height above the plane. If L- and T-dwarfs follow a similar scale-height as the M-dwarfs examined here ($z_0 \sim 300 \text{ pc}$), then contaminating dwarf stars at 1–2 kpc distance will be very rare, even before morphological selection.

7. CONCLUSIONS

1. Stars can be selected best using *SEXTRACTOR*'s half-light radius (r_{50}), corroborating previous identifications (Figures 8 and 17).
2. M-dwarfs can be reliably subtyped using near-infrared and optical color (Figure 14, Table 16).
3. Relatively more early-type M-dwarfs are identified in northern fields as opposed to southern Galactic ones. This confirms the dichotomy Pirzkal et al. (2009) noted (Table 9).
4. We report an overdensity in one of our fields, borg_1230+0750, consistent with the M-dwarf members of the Sagittarius stream at a distance of 20–25 kpc (Figure 22).
5. A naive, single-component fit of the vertical distribution of M-dwarfs shows a steady decline of scale-height, z_0 , with M-dwarf subtype (Figure 27).
6. The grouping of spurs of stars at different Galactic coordinates strongly hints at substructure in the Milky Way disk/halo of M-dwarfs (Figure 28).

8. FUTURE WORK

Future work with WFC3 (pure-parallel) programs on Milky Way dwarfs will use the ever-increasing number of sight-lines available to build a comprehensive catalog of M-, L-, and T-dwarfs belonging to the thin and thick disks and stellar halo of our Milky Way. New pure-parallel observational programs

with *HST*/WFC3 are needed to expand the number of sight-lines and improve statistics. At lower Galactic latitudes, this could easily be achieved with lower integration times than the BoRG or HIPPIES programs. Once such a proposed program is completed fully, the total tally of M-dwarfs should give a first idea of the size and shape of the Milky Way disks, thin and thick, and depending on the total statistics, the Galactic halo.

In parallel, spectroscopic identification of Milky Way dwarf stars can be done with the *HST*-3D near-infrared grism spectra (e.g., Brammer et al. 2012). The ongoing imaging and grism campaigns on the CANDELS fields (Koekemoer et al. 2011; Grogin et al. 2011) will improve the calibration of the photometric identifications of Galactic dwarfs in the pure-parallel surveys as well as add additional statistics to the star counts.

The general technique of morphologically identifying stars in space-based imaging, identifying dwarfs from near-infrared colors and subsequently subtyping these using an optical–near-infrared color will be perfectly suited for the *EUCLID* mission (Laureijs et al. 2011). The wide-band optical filter can be used to morphologically identify the stars and the three near-infrared filters to home in on the Galactic dwarfs. Finally, the optical–NIR color and complementary grism spectroscopy can then be used to subtype these dwarfs. With the wide survey area to faint point source sensitivity (all-sky 24 mag, 26 mag in deep fields) the *EUCLID* mission will yield an accurate measure of the shape and size of our Milky Way in subsolar dwarfs as well as an accurate census of halo substructure similar to the Sagittarius stream. Limiting factors may be the PSF in the near-infrared, leading to confusion issues, and the width of the optical filter, complicating subtyping. However, the two independent-angle grism spectra of all the objects in the field should unequivocally identify the Galactic dwarf stars.

Milky Way dwarfs are unlikely to be the focus of *James Webb Space Telescope* (*JWST*) observations, but they will certainly feature in them. The ubiquity of M-dwarfs in the BoRG fields points to their possible use as fine guidance for *JWST* image and NIRspec imaging/MOS registration.

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ERRATUM: “MILKY WAY RED DWARFS IN THE BORG SURVEY; GALACTIC SCALE-HEIGHT AND THE DISTRIBUTION OF DWARFS STARS IN WFC3 IMAGING” (2014, *ApJ*, 788, 77)

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ABSTRACT

In the catalog of M-dwarfs presented in Holwerda et al. (2014, H14 hereafter), there is an issue with the conversion from celestial coordinates to Galactic ones, done with PYEPHEM a wrapper around a trusted and vetted library *ephem*. Here we present the corrected coordinates (using *ASTROPY*) and distances based on AB magnitudes. We have amended the tables and figures accordingly. The relation between vertical scale-height (z_0) and M-dwarf subtype found in H14 is no longer present. We find a scale-height of 600 pc for all types, in part due to the presence of a second Galactic structural component.

1. MAPPING THE M-DWARF DISTRIBUTION

We re-computed the Galactic coordinates for the BoRG fields using the *ASTROPY* package (Astropy Collaboration et al. 2013) and the number of M-dwarfs in each, shown in the new Figure 22. The new values for all identified M-dwarfs are listed in Table 14. To estimate the distances to each M-dwarf, we compute the distance modulus from the inferred sub-type (and hence absolute magnitude) and the apparent magnitude in J_{F125W} from Hawley et al. (2002), converted from Vega magnitudes to AB. We compute the Galactic radius and height above the plane for all M-dwarfs, based on their Galactic longitude, latitude and the inferred photometric distances, assuming the position of the Sun 27 pc. above the plane and 8.5 kpc from the Galactic center.

The net difference with Holwerda et al. (2014, H14 hereafter) is that the vertical distribution observed for these M-dwarfs is much closer to the exponential drop-off one would expect for fields out of the plane of the Galaxy.

Figure 24 shows the vertical distribution of M-dwarfs color-coded by their Galactocentric radius. There is a clear disk component with all the M-dwarfs are ~ 6 –10 kpc from the center of the Milky Way and another component which shows a gradient with radius and is well above the plane of the disk. We now know this component to be the Halo part of the vertical distribution (van Vledde et al. 2016) but it is sometimes treated as the thick disk by other authors (e.g., Ryan & Reid 2016). This second component is much clearer in the corrected Galactic positions compared to H14. The majority of stars close to the plane of the disk are ~ 8 kpc from the center of the Galaxy. This is because the majority of BoRG fields are pointing out of the disk at an angle away from the Galactic Center (to avoid confusion with Galactic Objects) and thus probe the vertical extent of the disk close to the position of the Sun.

We assume there is no need to correct the densities in this part of the disk for the exponential decline with radius. Figure 24 does show a radial dependence of the outer parts of the vertical distribution on the radius. Our assumption is that the scale-height does not change significantly with radius, which is observed in external galaxies seen edge-on (Comerón et al. 2011a, 2011a, 2011c, Streich et al. 2016 in preparation).

We assume that the Galactic disk has the following parametric shape:

$$\rho(R, z) = \rho_0 \exp(-R/h) \text{sech}^2\left(\frac{z}{2 \times z_0}\right), \quad (1)$$

where $\rho(R, z)$ is the dwarf number density in a point in the disk, ρ_0 is the central number density, R is Galactocentric radius, h is the scale-length, z is height above the plane, and z_0 is the exponential scale-height of the disk. Figure 25 shows how the later-type M-dwarfs (M4-8) in the BoRG fields are concentrated in the thin disk and the earlier types (M0-3) probe both thin disk and the other component. We fit the sech^2 distribution to each photometric subtype, as well as early-, late- and all-types of M-dwarfs, summarized in the new Table 10 and the new Figures 26 and 27.

Figures 26 and 27 are significantly different from the versions in H14 in two ways: the relation between vertical scale-height (z_0) and M-dwarf subtype found in H14 is no longer present in Figure 27. Second, the densities inferred are much closer to the local (< 20 pc of the Sun) Reid et al. (2004) and Cruz et al. (2007) values (Figure 26). We note there is an offset of ~ 0.1 dex between our central density and the one implied by Reid et al. The likely culprit is the additional numbers of M-dwarfs in the secondary

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Figure 22. The Aitoff projection of the distribution of BoRG fields with the surface density of M-dwarfs of all types indicated. One field, borg_1230+0750 (star) stands out with 22 M-dwarfs (~ 5 stars arcmin $^{-2}$). We discard borg_1815-3244 (black circle) for its low latitudes and line-of-sight through the plane of the disk and close of the center of the bulge.

Figure 24. The volume density of M-dwarfs as a function as height above the plane of the Milky Way disk. The volume densities were normalized with a scale-length of 2.6 kpc and a depth of 1 pc at each star's position. Points are color-coded by the inferred Galactocentric radius. The majority of M-dwarfs are found close to the plane of the disk.

Figure 25. The volume density of M-dwarfs as a function as height above the plane of the Milky Way disk. Points and fits are color-coded by the M-dwarf sub-type.

Table 10
The Vertical Profile Fits to The Full Sample of Identified M-dwarfs

M-type (o)	ρ_0 (#/pc 3)	z_0 (kpc)
0	0.02	0.67 ± 0.73
1	0.19	0.84 ± 0.89
2	0.06	0.80 ± 1.31
3	0.60	0.61 ± 12.36
4	0.14	1.04 ± 0.67
5	0.77	0.67 ± 0.74
6	2.49	1.03 ± 5.42
7	...	...
8	181.04	-0.01 ± 0.02

Note. Values are Scaled so to be Compatible with Exponential Fits to The Galactic Profiles ($\rho_0/4$ and $z_0/2$).

Figure 26. The in-plane central density—the number of M-dwarfs belonging to the disk at the center of the Milky Way—for the best fit to the vertical distribution of M-dwarfs as a function of the M-dwarf subtype. The black circles are the values from Reid et al. (2008) for the immediate Solar neighborhood (< 20 pc), renormalized to the center of the Milky Way.

Figure 27. The scale-height ($z_0/2$) of the best vertical fit as a function of the M-dwarf subtype. Dashed lines are the uncertainty in the fit. A constant value of 600 pc would be consistent with most of these fits. This is $\sim 2\times$ greater than expected from previous work.

Table 14
The 274 M-dwarfs Identified in BoRG

ID	R.A.	Decl.	l	b	m_{F098M}	m_{F125W}	m_{F125W}	m_{F606W}	Mtype	modulus	dist	Height	Radius	Volume	Area
borg_0110-0224.551.0	17.501759	-2.418265	133.918256	-64.893095	23.82 ± 0.04	23.46 ± 0.02	23.28 ± 0.03	25.17 ± 0.09	2.04 ± 0.32	16.48	19.74	14.25	16.88 ± 1.85	228.43	10.88
borg_0110-0224.719.0	17.503586	-2.415663	133.921454	-64.890220	24.33 ± 0.05	23.97 ± 0.03	23.87 ± 0.04	25.83 ± 0.14	2.56 ± 0.50	16.73	22.16	15.99	17.90 ± 2.73	287.73	10.88
borg_0110-0224.820.0	17.528020	-2.411389	133.976421	-64.881854	19.68 ± 0.00	19.51 ± 0.00	19.45 ± 0.00	22.77 ± 0.01	7.30 ± 0.04	8.59	0.52	0.40	8.72 ± 0.01	0.16	10.88
borg_0110-0224.1016.0	17.553100	-2.408888	134.033565	-64.875102	24.54 ± 0.09	23.90 ± 0.04	23.72 ± 0.05	25.39 ± 0.13	1.30 ± 0.46	17.18	27.26	19.63	20.08 ± 3.83	435.66	10.88
borg_0110-0224.1414.0	17.559120	-2.400783	134.044244	-64.866085	24.08 ± 0.06	23.71 ± 0.06	23.44 ± 0.04	24.40 ± 0.05	-1.43 ± 0.27	17.26	28.31	20.37	20.52 ± 687.31	469.66	10.88

Table 15
The 1 T-Dwarfs Identified in BoRG

ID	R.A.	Decl.	l	b	m_{F098M}	m_{F125W}	m_{F125W}	m_{F606W}
borg_0540-6409.1929.0	84.862502	-64.152446	84.862502	-64.152446	22.9 ± 0.0	21.9 ± 0.0	22.2 ± 0.0	21.5 ± 0.0

Table 16
The 30 L-Dwarfs Identified in BoRG

ID	R.A.	Decl.	l	b	m_{F098M}	m_{F125W}	m_{F125W}	m_{F606W}
borg_0110-0224.1010.0	17.537240	-2.409470	17.537240	-2.409470	24.7 ± 0.1	23.7 ± 0.0	23.5 ± 0.0	25.3 ± 0.1
borg_0439-5317.882.0	69.836642	-53.263207	69.836642	-53.263207	24.0 ± 0.0	22.7 ± 0.0	22.2 ± 0.0	24.8 ± 0.9
borg_0540-6409.2993.0	84.876906	-64.132531	84.876906	-64.132531	25.0 ± 0.1	23.8 ± 0.0	23.4 ± 0.0	26.8 ± 0.6
borg_0751+2917.567.0	117.684321	29.285619	117.684321	29.285619	19.5 ± 0.0	17.8 ± 0.0	17.6 ± 0.0	19.6 ± 0.0
borg_0808+3946.457.0	122.094091	39.759095	122.094091	39.759095	25.0 ± 0.1	23.9 ± 0.0	23.5 ± 0.0	26.9 ± 0.6
borg_0819+4911.264.0	124.831743	49.175806	124.831743	49.175806	23.9 ± 0.0	22.8 ± 0.0	22.4 ± 0.0	27.9 ± 1.6
borg_0906+0255.462.0	136.409407	2.923645	136.409407	2.923645	24.4 ± 0.0	23.3 ± 0.0	22.8 ± 0.0	27.6 ± 0.8
borg_0909+0002.748.0	137.292821	-0.012257	137.292821	-0.012257	24.5 ± 0.1	23.2 ± 0.0	22.8 ± 0.3	26.6 ± 0.4
borg_0914+2822.673.0	138.558022	28.364206	138.558022	28.364206	24.8 ± 0.1	23.5 ± 0.0	23.1 ± 0.0	26.3 ± 0.3
borg_0926+4426.581.0	141.355847	44.425445	141.355847	44.425445	24.3 ± 0.0	23.1 ± 0.0	22.6 ± 0.0	25.2 ± 0.9
borg_1103-2330.623.0	165.819910	-23.506010	165.819910	-23.506010	23.9 ± 0.1	22.9 ± 0.0	22.5 ± 0.0	25.7 ± 0.2
borg_1111+5545.1125.0	167.747157	55.771759	167.747157	55.771759	23.6 ± 0.0	22.5 ± 0.0	22.1 ± 0.0	26.6 ± 0.3
borg_1153+0056.247.0	178.200215	0.922794	178.200215	0.922794	23.9 ± 0.0	22.9 ± 0.0	22.4 ± 0.0	26.2 ± 0.3
borg_1230+0750.2419.0	187.471709	7.820117	187.471709	7.820117	23.9 ± 0.1	22.8 ± 0.0	22.3 ± 0.0	26.2 ± 0.3
borg_1301+0000.1067.0	195.326828	0.013297	195.326828	0.013297	23.5 ± 0.1	22.2 ± 0.0	21.8 ± 0.0	24.3 ± 0.9
borg_1337+0028.1117.0	204.205278	-0.445870	204.205278	-0.445870	24.3 ± 0.2	23.1 ± 0.0	22.7 ± 0.0	25.3 ± 0.9
borg_1524+0954.24.0	231.044740	9.885957	231.044740	9.885957	24.9 ± 0.1	23.0 ± 0.1	22.8 ± 0.1	25.3 ± 1.0
borg_1632+3733.65.0	248.069017	37.540353	248.069017	37.540353	24.5 ± 0.0	23.3 ± 0.0	22.9 ± 0.0	28.5 ± 2.1
borg_1632+3733.349.0	248.080963	37.550065	248.080963	37.550065	23.5 ± 0.0	22.4 ± 0.0	22.0 ± 0.1	27.1 ± 1.4
borg_1632+3733.1325.0	248.076265	37.572819	248.076265	37.572819	24.3 ± 0.0	23.0 ± 0.1	22.5 ± 0.0	26.7 ± 0.5
borg_2132+1004.284.0	323.058751	10.068991	323.058751	10.068991	16.8 ± 0.0	15.0 ± 0.0	14.7 ± 0.0	17.2 ± 0.9
borg_2132+1004.332.0	323.060235	10.059801	323.060235	10.059801	21.2 ± 0.0	19.9 ± 0.0	19.7 ± 0.0	22.2 ± 0.9
borg_2155-4411.227.0	328.831076	-44.185153	328.831076	-44.185153	23.5 ± 0.0	22.5 ± 0.0	22.2 ± 0.0	24.8 ± 0.9
borg_2155-4411.974.0	328.809893	-44.164189	328.809893	-44.164189	24.3 ± 0.0	23.0 ± 0.0	22.5 ± 0.0	25.1 ± 0.9
borg_2351-4332.1314.0	357.668728	-43.514053	357.668728	-43.514053	25.2 ± 0.1	23.9 ± 0.0	23.5 ± 0.0	26.0 ± 0.9
borg_0456-2203.920.0	73.945566	-22.049396	73.945566	-22.049396	24.6 ± 0.1	23.4 ± 0.0	23.2 ± 0.0	24.4 ± 0.0
borg_1059+0519.644.0	164.717943	5.301323	164.717943	5.301323	24.4 ± 0.0	23.1 ± 0.0	22.6 ± 0.0	26.5 ± 0.3
borg_1118-1858.1915.0	169.392755	-18.972497	169.392755	-18.972497	24.8 ± 0.0	23.8 ± 0.0	23.3 ± 0.0	26.1 ± 0.1
borg_1459+7146.1298.0	224.751450	71.780685	224.751450	71.780685	24.8 ± 0.2	23.5 ± 0.0	23.1 ± 0.0	25.7 ± 0.1
borg_2132-1202.6461.0	322.941469	-12.021619	322.941469	-12.021619	24.6 ± 0.1	23.4 ± 0.0	23.0 ± 0.0	26.5 ± 0.4

Figure 28. The distribution of BoRG fields with the number of L-dwarfs indicated. Other symbols identical to Figure 22.

component well above the plane of the disk, i.e., we are including the density of Halo stars in our disk fit. A 0.1 dex offset suggest of order 10% of the stars in are, in fact, Halo stars (see also van Vledder et al. 2016).

The values in Figure 27 and Table 10 are still too high to be consistent with previous work on the vertical scale of stars in the thin disk. The vertical $sech^2$ profile does not describe the density distribution well above ~ 500 pc and this new distributions highlights the need to include another component well above and in addition to the disk.

For completeness, we include Figure 28 which shows the surface density of L-dwarfs selected by our morphology and color criteria.

2. CONCLUSIONS

The majority of conclusions for Holwerda et al. (2014) remain the same, only the last two change:

1. The secondary component visible in the vertical distribution of M-dwarfs is likely the Halo and not the thick disk of the Milky Way (Figures 24 and 25).
2. A naive, single-component fit of the vertical distribution of M-dwarfs shows no dependence on M-dwarf subtype and a scale-height for all M-dwarf subtypes that is still too high to be consistent with previous measures of the scale-height: $z_0 \sim 600$ pc, (Figure 27), a result of the second structural component.

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