The opacity of spiral galaxy disks. VI. Extinction, stellar light and color.

Benne W. Holwerda
University of Louisville

R. A. Gonzalez
Universidad Nacional Autónoma de México

P. C. van der Kruit
University of Groningen

R. J. Allen
Space Telescope Science Institute

Original Publication Information
Holwerda, B. W., R. A. Gonzalez, P. C. van der Kruit and R. J. Allen. "The Opacity of Spiral Galaxy Disks. VI. Extinction, Stellar Light and Color." 2005. *Astronomy & Astrophysics* 444(1): 109-117.

A&A 444, 109–117 (2005)
DOI: 10.1051/0004-6361:20053013

Astronomy & Astrophysics

The opacity of spiral galaxy disks

VI. Extinction, stellar light and color⋆

B. W. Holwerda[1,2], R. A. González[3], P. C. van der Kruit[1], and R. J. Allen[2]

[1] Kapteyn Astronomical Institute, University of Groningen, PO Box 800, 9700 AV Groningen, The Netherlands
[2] Space Telescope Science Institute, Baltimore, MD 21218 USA
e-mail: Holwerda@stsci.edu
[3] Centro de Radiastronomía y Astrofísica, Universidad Nacional Autónoma de México, 58190 Morelia, Michoacán, Mexico

Received 7 March 2005 / Accepted 7 September 2005

ABSTRACT

In this paper we explore the relation between dust extinction and stellar light distribution in disks of spiral galaxies. Extinction influences our dynamical and photometric perception of disks, since it can distort our measurement of the contribution of the stellar component. To characterize the total extinction by a foreground disk, González et al. (1998, ApJ, 506, 152) proposed the "Synthetic Field Method" (SFM), which uses the calibrated number of distant galaxies seen through the foreground disk as a direct indication of extinction. The method is described in González et al. (1998, ApJ, 506, 152) and Holwerda et al. (2005a, AJ, 129, 1381). To obtain good statistics, the method was applied to a set of HST/WFPC2 fields (Holwerda et al. 2005b, AJ, 129, 1396) and radial extinction profiles were derived, based on these counts. In the present paper, we explore the relation of opacity with surface brightness or color from 2MASS images, as well as the relation between the scalelengths for extinction and light in the I band. We find that there is indeed a relation between the opacity (A_I) and the surface brightness, particularly at the higher surface brightnesses. No strong relation between near infrared ($H-J$, $H-K$) color and opacity is found. The scalelengths of the extinction are uncertain for individual galaxies but seem to indicate that the dust distribution is much more extended than the stellar light. The results from the distant galaxy counts are also compared to the reddening derived from the Cepheids light-curves (Freedman et al. 2001, ApJ, 553, 47). The extinction values are consistent, provided the selection effect against Cepheids with higher values of A_I is taken into account. The implications from these relations for disk photometry, M/L conversion and galaxy dynamical modeling are briefly discussed.

Key words. radiative transfer – methods: statistical – ISM: dust, extinction – galaxies: ISM – galaxies: spiral – galaxies: photometry

1. Introduction

Dust extinction has influenced our perception of spiral disks since the first observations of them. The measurements of disk characteristics, such as the central surface brightness (μ_0), the typical exponential scale ($r_{\rm typ}$) and the mass-to-light ratio (M/L), are all affected by the dust extinction in the photometric band of observation. The original assertion by Holmberg (1958) that spiral disks are optically thin to their stellar light came under scrutiny after the paper by Disney (1990) and the observational result of Valentijn (1990) revealed that they were, in fact, practically opaque. The debate quickly culminated in a conference (Davies & Burstein 1995), during which many methods to measure the opacity of spiral disks were put forward. Notably, two methods do not use the disk's own stellar light for the measurement: the occulting galaxy technique (White & Keel 1992; Andredakis & van der Kruit 1992) and the use of calibrated counts of distant objects (the "Synthetic Field Method" (SFM), by González et al. 1998). Thus far, the following picture of the influence of dust on disk photometry has emerged from earlier studies, most of which are based on the inclination effect on photometry of a large sample of spiral disks. Tully et al. (1998) and Masters et al. (2003) reported that disks are more opaque in the blue. Disks are practically transparent in the near infrared (Peletier & Willner 1992; Graham 2001), making these bands the best mass-to-luminosity estimator (de Jong 1996). Disks are practically transparent in the outer parts but show significant absorption in the inner regions (Valentijn 1994; Giovanelli et al. 1994). The radial extent of the dust has been explored using the sub-mm emission (Alton et al. 1998b; Davies et al. 1999; Trewhella et al. 2000; Radovich et al. 2001) and edge-on models (Xilouris et al. 1999). These results indicate that the scalelength of the dust is 40% larger than that of the light. The disk's average extinction correlates with the total galaxy luminosity (Giovanelli et al. 1995;

⋆ Research support by NASA through grant number HST-AR-08360 from the Space Telescope Science Institute (STScI), the STScI Discretionary Fund (grant numbers 82206 and 82304 to R. J. Allen) and the Kapteyn Institute of Groningen University.

Tully et al. 1998; Masters et al. 2003). And spiral arms are more opaque than the disk (Beckman et al. 1996; White et al. 2000).This may be attributed to a more clumpy medium in the arms in addition to a disk (González et al. 1998). Stevens et al. (2005) found evidence based on the infrared and sub-mm emission from dust for two thermal components of the dust, a warm component associated with star formation and a colder component in a more extended disk.

In this paper we explore the relation between the light from a spiral galaxy's disk and the opacity measured using the SFM. This paper is organized as follows: Sect. 2 summarizes the "Synthetic Field Method", Sect. 3 discusses possible systematic effects in the method and sample, Sect. 4 describes the relation between surface brightness and average extinction, Sect. 5 explores this relation for arm and disk regions, and Sect. 6 the relation between extinction and near-infrared color. In Sect. 7, the scalelengths for light and extinction are compared. A brief comparison between Cepheid reddening and opacity is made in Sect. 8. The implications for measurements involving spiral disks are discussed in Sect. 9, and we list our conclusions in Sect. 9.

2. The "Synthetic Field Method"

The number of distant galaxies seen through a foreground spiral disk is a function of dust extinction as well as crowding and confusion in the foreground disk. Distant galaxy numbers were used by several authors to measure extinction in the Magellanic Clouds and other galaxies[1]. The "Synthetic Field Method" was developed by González et al. (1998) to calibrate an extinction measurement based on the number of distant galaxies in a Hubble Space Telescope (HST) image. It quantifies the effects of crowding and confusion by the foreground spiral disk. The SFM consists of the following steps. First, the number of distant galaxies in the science field is identified. Secondly, synthetic fields are constructed. These are the original science field with a suitable deep field added, which is dimmed to mimic the effects of dust. The added distant galaxies in the resulting synthetic field are identified, based on object appearance and color. The number of these synthetic galaxies identified in the synthetic fields as a function of dimming can then be characterized:

$$A = -2.5\, C\, \log\left(\frac{N}{N_0}\right) \cdot \qquad (1)$$

A is the dimming in magnitudes, N the number of synthetic galaxies retrieved. N_0 is the number of galaxies expected in the science field if no extinction were present and C is the parameter of the fit that depends on the crowding and confusion of the science field. A series of synthetic fields at varying values for A is made to accurately characterize Eq. (1) for every science field in question. From the relation above and the number of actual distant galaxies identified in the science field, the average extinction in the field can be determined. As the cosmic variance causes an additional uncertainty in the original number of distant galaxies present behind the foreground disk, the uncertainties in the extinction determination are high for individual fields. For a complete discussion of the uncertainties of the SFM, see Holwerda et al. (2005a). To combat poor statistics, the numbers of distant galaxies in several images are combined, based on common characteristics of the foreground disks. Holwerda et al. (2005b) combined numbers based on radius and Hubble types. In this paper we compare the numbers of distant galaxies for image sections of common surface brightness and color.

González et al. (2003) and Holwerda et al. (2005c) concluded that the optimal distance for the SFM is that of Virgo cluster for the HST instruments. Hence our sample of fields is taken for disks at this range of distances.

3. Discussion of systematic effects

There are two possible sources of systematics in the following results: the selection of the sample of foreground galaxies and possible systematics in the method itself. The systematics and uncertainties of the method are also discussed in detail in Holwerda et al. (2005a) but we briefly list possible systematics here. The selection of the sample is discussed in Holwerda et al. (2005b) but the effects of the smaller sample on the new segmentation of distant galaxy counts are discussed below.

3.1. Systematics of the Synthetic Field Method

A systematic can creep into the SFM if there is a difference in the object identification in the science and the synthetic fields. This was one of our main drivers to automate the identification process to the highest possible degree. However, a visual check of the candidate objects is still necessary. Therefore an observer bias can not be completely excluded. See for an in-depth discussion regarding the identification process Holwerda et al. (2005a).

There are, however, several reasons why we consider the counts calibrated sufficiently for any systematics. The radial opacity profile does seem to end at zero extinction at higher radii (Holwerda et al. 2005b). The radial opacity profile agrees with the values from occulting galaxies (Holwerda et al. 2005b). And there is good agreement by different observers on the counts in NGC 4536 (Holwerda et al. 2005a). The Synthetic Field Method was conceived to calibrate any observer bias. If our identification process has resulted in the removal of blue distant galaxies together with the HII regions, this has been done in the same way for both synthetic and science fields and therefore does not affect the derived opacity value.

3.2. Sample selection effects

Since the SFM requires that we combine several foreground galaxies in order to obtain the required statistics on the distant background galaxies, there is the risk of selection effects in our results. The selection criteria for the data-sets in our sample are described in detail in Holwerda et al. (2005b). Essentially face-on spiral galaxies with deep V, I WFPC2 data available are selected. To ensure that the galaxy sample does not display two clearly separate populations in central surface brightness or color, the histograms of central magnitude and morphological

[1] See for a brief review Holwerda et al. (2005a).

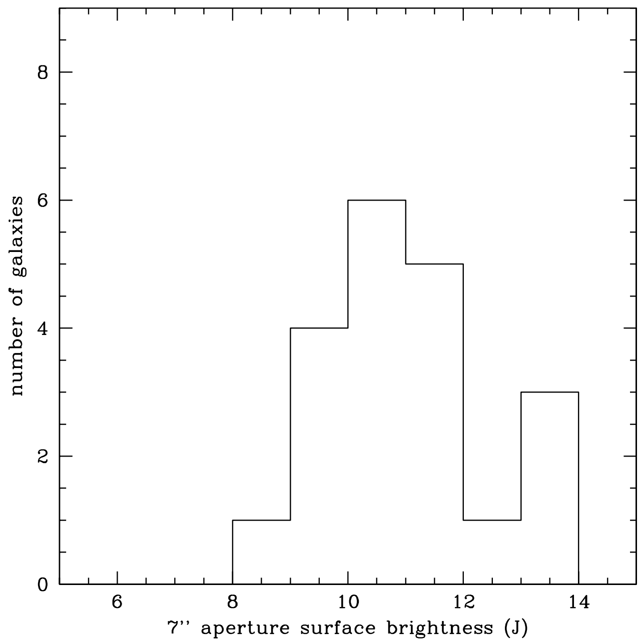

Fig. 1. The number of foreground galaxies as a function of 2MASS small aperture (7″) magnitude from the Large Galaxy Atlas (Jarrett et al. 2003).

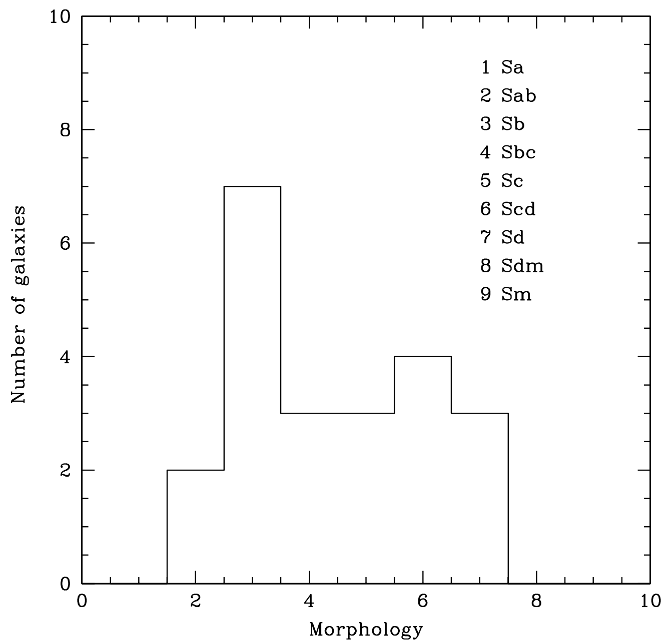

Fig. 2. The histogram of the Hubble types in this paper's sample. The HST Distance Scale Key project selected in favour of late-type spirals. However, most spiral galaxy types later then Sab are in our sample.

type are plotted in Figs. 1 and 2. There is no clear indication for a bimodal distribution in the central surface brightness. There is, however, a selection effect against the earliest type spirals in our sample as these were not selected for the HST Distance Scale Key project.

The opacities from the SFM are not readily corrected for the inclination of the disk as this correction depends strongly on the dust cloud morphology (Holwerda et al. 2005b; Holwerda 2005). The opacity values can therefore best be interpreted as an upper limit of the apparent filling factor of clouds.

From our original sample (Holwerda et al. 2005b), the following fields could not be used due to problems with the 2MASS fields (M51-2, NGC 4321 NGC 4414-1/2, NGC 4496A, NGC 4571, NGC 4603, NGC 4639 and NGC 4725). The two LSB galaxies (UGC 2302 and UGC 6614) were excluded as well. The numbers from the remaining 23 fields are used in Figs. 5 through 8. There is a spread in morphological types in these galaxies (Fig. 2), a factor to take into account in the interpretation of the following results.

4. Surface brightness and disk opacity

Giovanelli et al. (1994), Tully et al. (1998) and Masters et al. (2003) linked the overall disk opacity with the total luminosity of a spiral galaxy. It appears that the brighter spiral disks are also more opaque. The classical relation between gas, dust and stellar mass in the Milky Way is often used as a benchmark. If there is a constant ratio between stars and dust, some relation is expected between surface brightness and opacity of a spiral disk. The relation between light and extinction can be explored in more detail, using the SFM. Holwerda et al. (2005b) compared the average radial opacity of their sample to the average radial surface brightness and found a tentative relation between the surface brightness of a radial annulus and its opacity based on counts of field galaxies (Fig. 16 in Holwerda et al. 2005b).

The computation of an average surface brightness per radial interval, integrated over all these disks, smoothes all the variations in surface brightness. To explore any relation between surface brightness and opacity without this smoothing, the counts of distant galaxies must be done for a surface brightness interval, not a radial one.

Each of the distant galaxies found in either synthetic or science fields was flagged with the surface brightness of the corresponding position in the 2MASS (Jarrett et al. 2003) image in the *H*, *J* and *K* bands. This allows us to sort the distant galaxies according to disk surface brightness, regardless of their position in the foreground disk. In Figs. 3–5 we plot the opacity versus surface brightness in the *H*, *J*, and *K* band respectively. The top panels show the number of field galaxies found at each surface brightness, both in the science field and the synthetic fields without any extinction ($A = 0$). In Figs. 3–5, the middle panel shows the opacity without distinguishing for arm and disk. The bottom two panels show the derived opacity from the counts in just the spiral arm or disk regions respectively.

The drop of the number of synthetic distant galaxies without extinction at higher surface brightnesses is a selection effect of the HST data. The majority of the WFPC2 images are pointed at the optical disks of the galaxies, leaving little solid angle at the lower radii, and hence high surface brightness. In addition, crowding effects limit useful solid angle at higher surface brightnesses. The limit of the 2MASS photometry is also quickly reached at low surface brightnesses, the zeropoints are around 20,5 for both *H*, *K* and 21 for *J*. As a result, the statistics are sufficient for an opacity measurement between approximately 18 to 21 mag arcsec^{-2} in *H* and *K* and 19 and 21 for *J*.

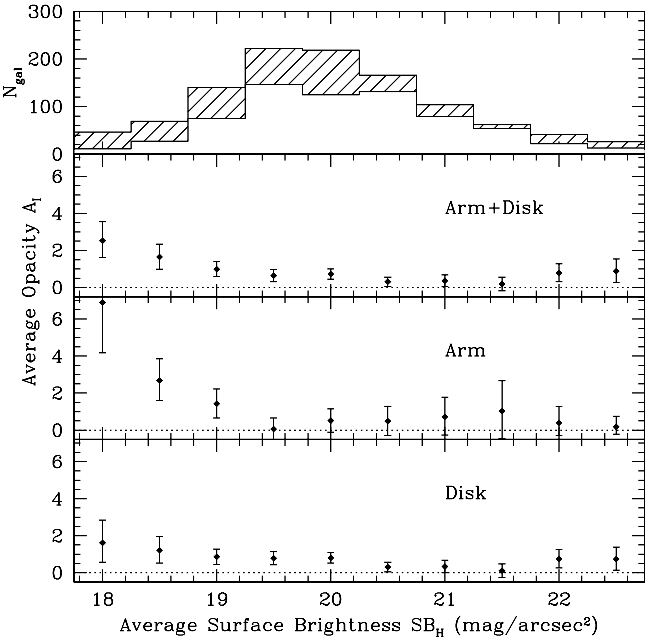

Fig. 3. *Top*: the number of field galaxies as a function of 2MASS surface brightness: the distant galaxies from the science field (solid) and the synthetic fields (shaded) without dimming ($A = 0$). Second from the top: the opacity in I (F814W), in magnitudes, as a function of H-band surface brightness in 2MASS (Kleinmann et al. 1994) images. The point at 17.5 mag arcsec^{-2} is not based on sufficient statistics for a good comparison. Third from the top: the opacity in I as a function of H-band surface brightness, for those regions classified as "spiral arm". *Bottom*: the opacity in I as a function of H-band surface brightness, for those regions classified as disk region, not part of a spiral arm.

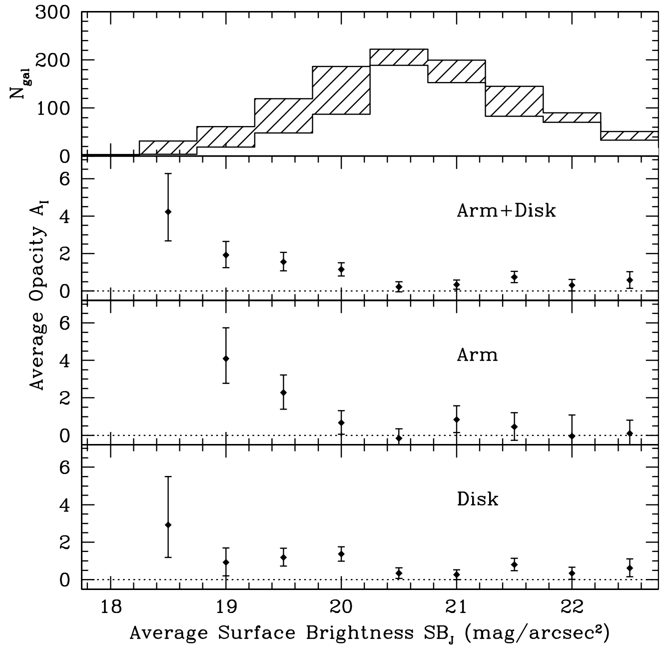

Fig. 4. *Top*: the number of field galaxies as a function of 2MASS surface brightness; the distant galaxies from the science field (solid) and the synthetic fields (shaded) without dimming ($A = 0$). Second from the top: the opacity in I (*F814W*), in magnitudes, as a function of J-band surface brightness in 2MASS (Kleinmann et al. 1994) images. Third from the top: the opacity in I as a function of J-band surface brightness, for those regions classified as "spiral arm". Bottom: the opacity in I as a function of J-band surface brightness, for those regions classified as disk region, not part of a spiral arm.

The surface brightness values were derived from the public 2MASS images, as they are relatively uniform and the near infrared emission tracks the stellar component of the disk better than other bands. There are two main concerns in using the 2MASS public images to compute surface brightnesses. The first concern is whether or not the photometry of them can be compared over a series of images and how accurate a surface brightness measurement from a single pixel in these images is. Secondly, significant flux might be contributed by the detected field galaxies themselves as a distant galaxy identified in the WFPC2 field is about a pixel in size in the 2MASS field. If this is the case, the surface brightness measurements of the science field galaxies should be generally higher than for galaxies in the synthetic fields, where there is no actual distant background galaxy to contribute to the 2MASS flux. The first concern can be addressed by simply comparing over large surface brightness bins and by using only similar measurements, i.e. the surface brightness measurements for the synthetic fields have the same photometric uncertainty as the science field ones. The effect of the second concern should be evident from the relative distribution of the number of galaxies from the science and synthetic fields as a function of surface brightness. If there is a systematic offset between these two groups, the distant galaxies in the science fields did contribute to the flux. Such an offset of the science field objects to the higher surface brightnesses should be evident in the histograms in Figs. 3–5. None seems to be present. Any such offset would work counter to the result of higher opacity with brighter disk surface brightness that was found. As an extra check, Fig. 6 shows the same as Fig. 5 but for a smaller bin size in surface brightness. In Fig. 6, an offset is not evident as well and the same general trend can be discerned between surface brightness and opacity.

By setting the bin-size in surface brightness much larger than the expected surface brightness uncertainty, the scatter in the opacity is significantly reduced. For this reason we chose a bin size of 0.5 mag for Figs. 3–5. The uncertainty in the number of distant galaxies depends on the solid angle under consideration. The uncertainties in Figs. 3–6 are based on the total solid angle in the whole of the mosaics with a surface brightness value in the interval. A reliable observation could be made for surface brightnesses fainter than approximately 18 mag arcsec^{-2} in either H or K and 19 in J.

In all three plots, there is an interval where the opacity is constant with surface brightness but there is a clear upturn in opacity at the brighter values. As the surface brightness limits the accuracy of the SFM (Holwerda et al. 2005c), these opacity values are also more uncertain. However, the result is consistent with studies of inclination effects on disks (Giovanelli et al. 1994; Masters et al. 2003) and with Freeman's Law (Freeman 1970).

Whether or not the spread in Hubble types (Fig. 2) has a discernible effect on the relation between surface brightness and opacity can be found by determining the relations for the early

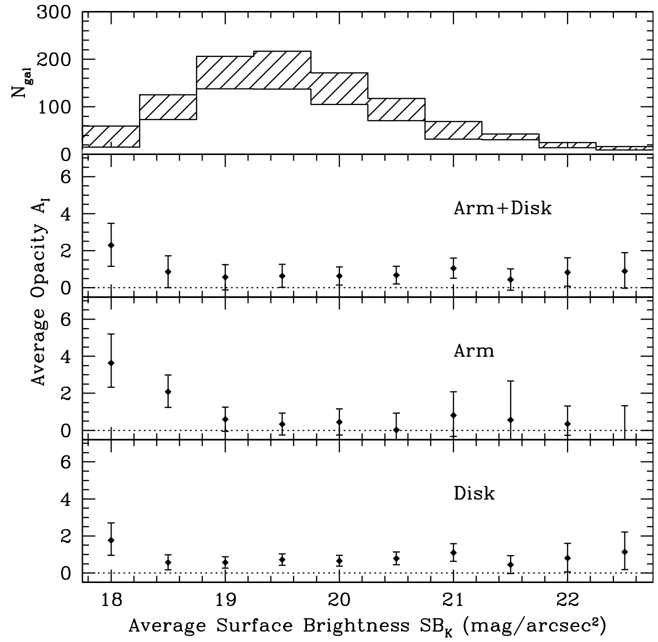

Fig. 5. *Top*: the number of field galaxies as a function of 2MASS surface brightness; the distant galaxies from the science field (solid) and the synthetic fields (shaded) without dimming ($A = 0$). Second from the top: the opacity in I (*F814W*), in magnitudes, as a function of K-band surface brightness in 2MASS (Kleinmann et al. 1994) images. Third from the top: the opacity in I as a function of K-band surface brightness, for those regions classified as "spiral arm". *Bottom*: the opacity in I as a function of K-band surface brightness, for those regions classified as disk region, not part of a spiral arm.

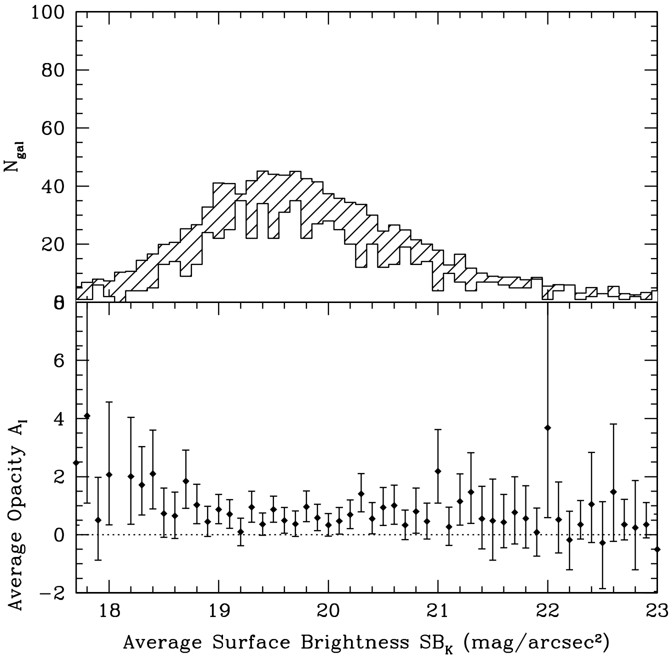

Fig. 6. *Top panel*: the number of field galaxies as a function of 2MASS surface brightness, but at a much smaller sampling scale than Fig. 5. The distant galaxies from the science field (solid) and the synthetic fields (shaded) without dimming ($A = 0$). *Bottom*: the opacity in I (*F814W*) in magnitudes, as a function of K-band surface brightness in 2MASS (Kleinmann et al. 1994) images.

and late type spirals in our sample. The relations for early and late types do not appear to be any different in all of the 2MASS bands.

5. Surface brightness and opacity in arm and disk

In Figs. 3–5, the relation between surface brightness in the H, J, and K bands and opacity for the arm and disk regions is also shown. In Holwerda et al. (2005b), a relation between the averaged surface brightness and extinction in radial annuli was suspected. In the case of spiral arms this relation could be steeper than in the rest of the disk. In Figs. 3–5 the opacities are derived as for arms and disk combined, and separately for the sections that were classified as arm or as disk-regions, either inter-arm or outside-arm. Classifications of the regions are based on the WFPC2 mosaic and are described in Holwerda et al. (2005a) and Holwerda (2005). Opacity measurements can be made for regions fainter than approximately 18 mag arcsec^{-2} in either H, J or K, where the brightest disk regions are inter-arm regions close to the center. Bright regions are also in the middle of spiral arms, notably in star forming regions.

The relation between opacity and surface brightness shown in Figs. 3–5 seems to be dominated by the arm regions in these fields. There is a steep relation between opacity and surface brightness in the arms, while there is none or perhaps a weak one in the disk regions. Since the measured opacity by the SFM is an average for the given area, the higher value for brighter arm regions indicates a higher filling factor – or surface density – of molecular clouds in these regions. The average values of A are consistent with those found by Valentijn (1990) but are uncorrected for inclination. The brighter regions in the spiral arms are in the middle of the spiral arm and near the galaxy's center. This higher surface density of dust clouds is consistent with models which interpret spiral arms as local overdensities of molecular clouds and associated starformation.

6. Disk opacity and NIR color

In a similar fashion as the counts of distant galaxies from science and synthetic fields are grouped using the disk's surface brightness in 2MASS images, the color of the foreground disk can be used. As this color is based on a 2MASS pixel for each distant galaxy, the errors are likely to be substantial and it is possible that the distant galaxy in the science field itself can influence this color more than the surface brightness.

To compensate for the added uncertainty, the sampling of color is taken to be 1.0 mag. In Figs. 7 and 8, the opacity in I as a function of the disk's $H - K$ and $J - K$ colors are plotted respectively. From these figures we conclude that there is very little or no relation between the reddening of the disk in the near-infrared bands and the average opacity of the disk in I.

The motivation for this comparison is the common use of near-infrared color as an indicator of stellar mass-to-light ratio. A lack of a strong trend of color with opacity would warrant this use. Since the comparison in Figs. 7 and 8 is limited to a small range in color, the only conclusion is a lack of a strong relation.

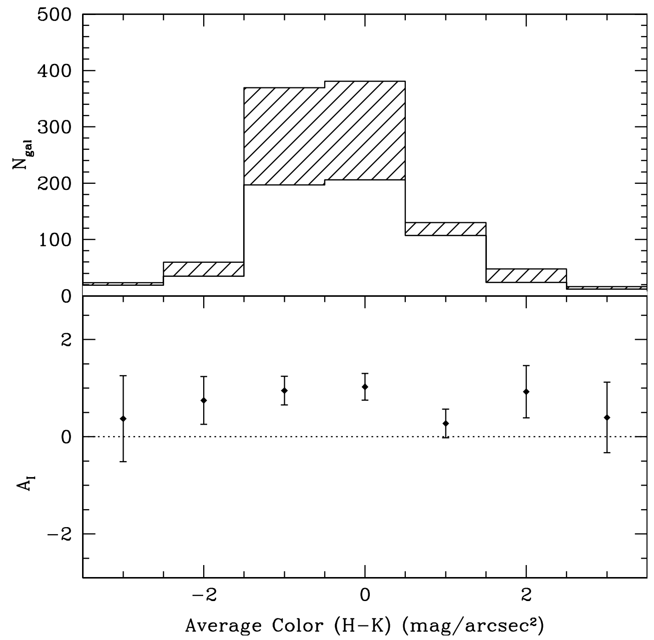

Fig. 7. The relation between $(H - K)$ color and I-band extinction (*bottom*). Top panel shows the number of distant galaxies for each color bin.

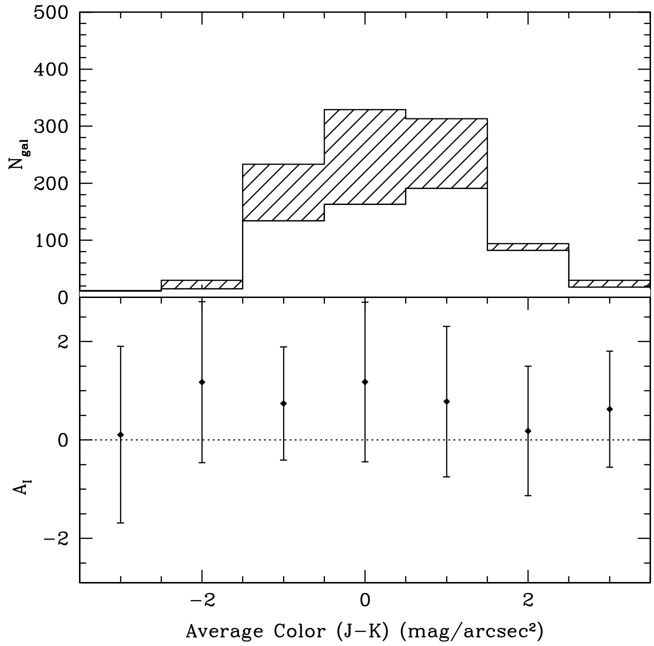

Fig. 8. The relation between $(J - K)$ color and I-band extinction (*bottom*). Top panel shows the number of distant galaxies for each color bin.

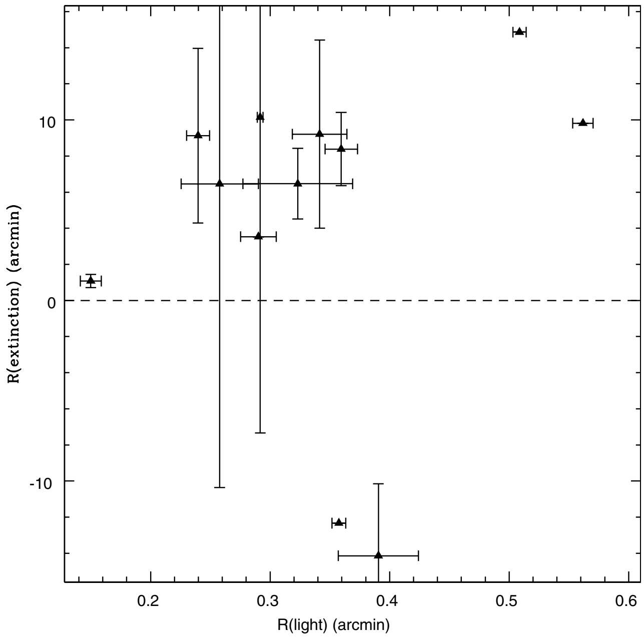

Fig. 9. The scalelengths of extinction and light in the I band for those galaxies in both our sample that of Macri et al. (2000). Most of scalelengths of the dust are much larger than those of the light, contrary to earlier results but a few are negative.

7. Dust and light scalelengths

A subject of interest is the extent of dust in spiral disks. In Holwerda et al. (2005b), we presented radial profiles of individual WFPC2 fields as well as averages over Hubble type and arm/disk regions. A common indicator of disk scale is the exponential scalelength of the radial light profile. Macri et al. (2000, 2005) present photometry and exponential disk fits on the Distance Scale Key Project spiral galaxies in order to provide a calibration for the Tully-Fisher relation. They present photometric diameters, scalelengths and central surface brightnesses in B, V, R and I for a large subset of our sample.

A simple exponential disk was fitted to the radial extinction measurements of individual fields presented in Table 3 of Holwerda et al. (2005b). These values are poorly determined as the small field-of-view of the WFPC2 results only in a few opacity measurements per galaxy. Some of the extinction profiles rise, rather than decline. This is the result of the presence of spiral arms in the relevant WFPC2 images.

Figure 9 compares the scalelengths for the light and extinction in I for individual galaxies. The scalelengths and the R_{25} (de Vaucouleurs et al. 1991) are also listed in Table 1. These scale-lenghts of the opacity are an order of magnitude larger than the scale-lengths of the stellar light. This is a direct result of the very gradual decline with radius seen in Holwerda et al. (2005b).

This would be in contradiction to results from edge-on galaxies on dust scalelengths which put it at 1.4 times the scalelength of the stars (Xilouris et al. 1999; Radovich et al. 2001) but not inconsistent with sub-mm observations which put the scale of the dust disk somewhere between the HI and stellar scales (Alton et al. 1998b; Davies et al. 1999; Trewhella et al. 2000).

One explanation for our result could be that the Cepheid distance project pointed the HST at the arms of these galaxies, biasing the extinction profile. However, it seems likely that a dark, cold cloud component displays a different relation with radius than that obtained from previous measurements of dust via IR emission (warm dust, illuminated by stars) or stellar reddening (diffuse dust). This is consistent with the picture of the ISM of spiral disks emerging since the first results by

Table 1. The scalelengths of the galaxies from the Hubble Distance Scale Key Project. Stellar scalelengths from Macri et al. (2005) and dust scalelengths from fitted to the points in Holwerda et al. (2005b).

Galaxy	R_{typ}(light) arcmin	err	R_{typ}(dust) arcmin	err	R_{25} arcmin
NGC 925	0.588	0.042			10.47
NGC 1365	0.499	0.012			11.22
NGC 1425	0.292	0.002	10	17	5.75
NGC 2541	0.341	0.023	9	5	6.31
NGC 2841	0.358	0.006	–12		8.13
NGC 3198	0.290	0.015	3.5		8.51
NGC 3319	0.323	0.046	6.5	2.0	6.17
NGC 3351	0.391	0.033	–14.1	4.0	7.41
NGC 3621	0.410	0.029			12.3
NGC 3627	0.450	0.011			9.12
NGC 4414	0.258	0.032	6	17	3.63
NGC 4535	0.360	0.014	8.4	2.0	6.17
NGC 4536	0.305	0.007			7.59
NGC 4548	0.240	0.010	9.1	4.8	5.37
NGC 4639	0.150	0.009	1.1	0.4	2.75
NGC 4725	0.562	0.008	9.8		10.72
NGC 7331	0.509	0.006	15		10.47

Table 2. Opacity of the WFPC2 field from Cepheid reddening and Galaxy counts.

Galaxy	$E(V-I)$	$\sigma\, E(V-I)$	$A_{\rm Cepheid}$	$A_{\rm SFM}$
NGC 925	0.21	0.02	0.8	$-0.4^{+0.3}_{-0.3}$
NGC 1365	0.20	0.02	0.8	$0.5^{+0.3}_{-0.3}$
NGC 1425	0.16	0.03	0.6	$0.5^{+0.3}_{-0.3}$
NGC 2541	0.20	0.02	0.8	$0.8^{+0.3}_{-0.3}$
NGC 3198	0.15	0.04	0.6	$0.8^{+0.3}_{-0.3}$
NGC 3319	0.13	0.04	0.5	$0.9^{+0.4}_{-0.4}$
NGC 3351	0.24	0.04	1.0	$1.2^{+0.5}_{-0.6}$
NGC 3621-OFF	0.36	0.04	1.4	$1.0^{+0.3}_{-0.4}$
NGC 3627	0.24	0.03	1.0	$2.1^{+0.7}_{-0.7}$
NGC 4321	0.22	0.03	0.9	$2.3^{+0.7}_{-0.8}$
NGC 4414-2	0.15	0.04	0.6	$0.7^{+0.3}_{-0.4}$
NGC 4496A	0.14	0.01	0.6	$5.0^{+0.8}_{-0.9}$
NGC 4535	0.19	0.02	0.8	$0.7^{+0.4}_{-0.4}$
NGC 4536	0.18	0.02	0.7	$0.9^{+0.4}_{-0.4}$
NGC 4548	0.18	0.04	0.7	$0.8^{+0.3}_{-0.4}$
NGC 4639	0.12	0.04	0.5	$0.8^{+0.3}_{-0.3}$
NGC 4725	0.29	0.03	1.2	$0.8^{+0.3}_{-0.3}$
NGC 7331	0.25	0.05	1.0	$0.3^{+0.3}_{-0.3}$

Valentijn (1990) (e.g. Block et al. 1994 and FIR observations Nelson et al. 1998; Alton et al. 1998a; Trewhella et al. 2000; Popescu et al. 2002; Hippelein et al. 2003). In addition, the general assumption that the dust is distributed as an exponential disk might need to be revisited.

Future work with FIR/sub-mm observations or counts of background galaxies should characterise the scale and radial profile of dust disks in spiral galaxies. An improved measurement of the dust scalelength from galaxy counts would require a larger solid angle per individual galaxy.

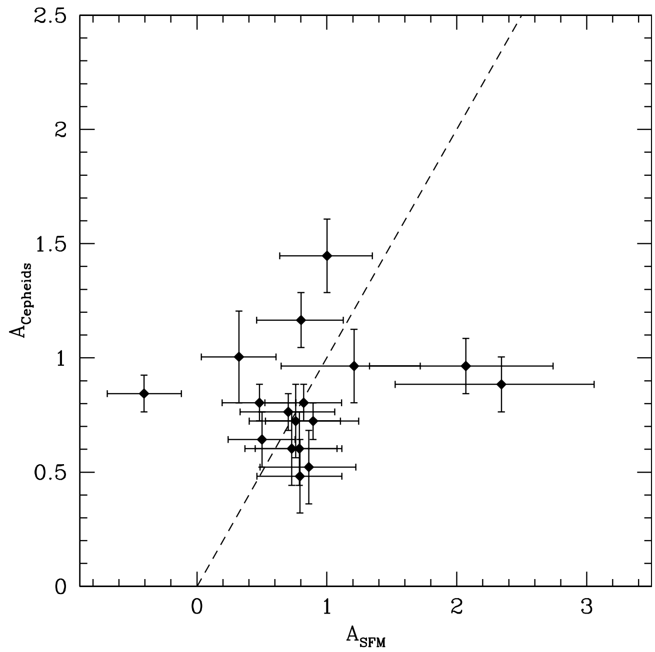

Fig. 10. The average extinction derived from the number of distant galaxies compared to the extinction derived from the Cepheid reddening ($E(V-I)$) from Freedman et al. (2001). There is no clear linear relation (dashed line). The Cepheid extinctions saturate at higher opacities as the Distance Scale project selected against high-extinction Cepheids. Note that cosmic variance in the number of background galaxies can produce a negative opacity value.

8. Comparison to Cepheid reddening

Freedman et al. (2001) present reddening values ($V-I$) based on the photometry of the Cepheids in the Distance Scale Key Project galaxies. The reddening $E(V-I)$ was converted to an opacity in I using the Galactic Extinction Law. In Table 2 and Fig. 10 the average extinction values from number counts for the combined Wide Field chips in each galaxy and the average extinction derived from the Cepheid reddening are compared. The comparison is not a straightforward one. The extinction in front of a Cepheid variable is local and biased against high extinction values. Freedman et al. (2001), however, gave average reddening based on all Cepheids in the field. The extinction from the number of distant galaxies is for the entire height of the disk and an average for all the chips.

In Fig. 10, the scatter in $A_{\rm Cepheid}$ for a given $A_{\rm SFM}$ value can be explained by variations in the average depths of the Cepheids in the disks; the lack of high $A_{\rm Cepheid}$ values is probably the result of the detection bias for Cepheids. The opacity from the number of distant galaxies can probe much higher average extinction, something the Cepheid reddening selects against.

9. Discussion: implication for our view of spiral disk

The primary result presented in this paper is the relation between near-infrared surface brightness and disk opacity. Such a relation is consistent with the observation that brighter galaxies are also more opaque (e.g. Masters et al. 2003). It is also consistent with "Freeman's Law" (Freeman 1970)): the central surface brightness of the disk is constant, regardless of the inclination. A direct relation between surface brightness and disk extinction has some ramifications for photometric measurements of spiral disks. The slope of the light profile of a spiral disk is underestimated as more light is hidden by dust in the brighter parts. As a result, the scalelength of the exponential disk is overestimated. This has implications for dynamical models of spiral disks. If the stellar disk is in fact somewhat more compact than observed, the stellar mass contribution of this disk is greater in the center. To model rotation curves, it is common to assume a "maximum disk": the light profile is converted to a mass distribution using the maximum conversion factor allowed by the rotation curve. If surface brightness and extinction are related, as Figs. 3–5 indicate, then the stellar mass estimate is underestimated in the center of the disk. The stellar profile, corrected for extinction, would mitigate the need for dark matter in the center of spiral disks. A stellar mass profile, corrected for extinction, would reach the point of "maximum disk" at a slightly shorter radius and at a lower M/L conversion factor (see also Gonzalez-Serrano & Valentijn 1991). A different M/L ratio for the "maximum disk" would imply a slope of the Tully-Fisher relation, slightly lower than 3.5, according to Bell & de Jong (2001).

The second result in this paper is the lack of a strong relation between surface brightness and opacity in the part of the disk outside the spiral arms. This constant opacity value for the disk is consistent with the flat average radial profile for the disk regions, that we found from the same data (Holwerda et al. 2005b). However, this result is predominantly limited to the optical disk of the galaxies. The constant opacity as a function of surface brightness and radius suggests to us that this component may extend to a point beyond the optical radius of the disk. Evidence for a cold disk with warmer dust in the arms has been found from emission (Popescu et al. 2002; Hippelein et al. 2003). However, the actual extent of this dust component can be explored with counts of galaxies in many fields of a single disk -instead of an average over several disks.

The spiral arms show a stronger relation between surface brightness and opacity. This would be consistent with the view that the arms are overdensities in the disk. The fact that the relation between surface brightness and opacity is different for arm and disk regions, implies different dust components. As a result, a single exponential disk may be an oversimplification of the general dust distribution.

The third result is that no strong relation between NIR color and dust opacity seems to be present. This is consistent with the results of Bell & de Jong (2001). They find that a good indicator of the M/L in a spiral disk is its near-infrared color. They also discuss effects of dust on their models but the effect of dust reddening and dimming is estimated to cancel out to first order. Bell & de Jong (2001) advise against using their M/L values for anything but a whole disk, as local extinction is likely to be patchy and more grey in nature. In fact, Bell & de Jong (2001) already allow for sub-maximum disks as a shift in their zero-point in the relation between M/L and color. Recent work on rotation curves of spiral disks, such as Kassin & de Jong (2005), should therefore not be affected by the use of the color for the M/L indicator, provided the profile is determined predominantly outside the spiral arms.

10. Conclusions

The main conclusions we can draw from the numbers of distant galaxies seen through a spiral disk, as analysed in this paper are:

1. The dust opacity of the spiral disks increases with increasing surface brightness of the disk (Figs. 3–5).
2. This effect is mainly restricted to the spiral arms. This implies a higher surface density of clouds in the spiral arms. (Figs. 3–5).
3. For the disk regions, the opacity is constant with surface brightness (Figs. 3–5).
4. The dust opacity does not strongly correlate with the near-infrared color of the foreground disk (Figs. 7 and 8).
5. An exponential disk appears to be a poor description of the dust distribution as evident from the much larger values compared to the stellar scalelength (Fig. 9) but better counts on single galaxies should should provide a better constraint.
6. The average values of the Cepheid reddening and the disk opacity correspond reasonably well for the lower extinction values. High disk extinction does not show in the Cepheid reddening, probably due to selection effects (Fig. 10).

If surface brightness and disk opacity are linked, fitting a maximum M/L to the light distribution to model the stellar dynamical component ("Maximum Disk") is an unrealistic approach. In addition, this could explain the results from Giovanelli et al. (1994) and Masters et al. (2003) and "Freeman's Law" as well. The grey behaviour of the opacity as measured from numbers of distant background galaxies can be explained by the fact that the observable distant galaxies are on low extinction lines-of-sight. The fact that the opacity is related to the surface brightness of the disk does pose a problem for the use of a single M/L value in dynamical fits.

The Advanced Camera for Surveys on Hubble has imaged many more galaxies and the presented relation between surface brightness and extinction could be further explored using these more recent data. Any systematic effect of combining counts from several different disks can be avoided altogether in a similar analysis performed on a single disk. However, as González et al. (2003) and Holwerda et al. (2005c) point out, the SFM is limited to the less crowded parts of the disk and the relation between extinction and surface brightness could only be extended at the fainter end.

Acknowledgements. The authors would like to thank the referee, Edwin Valentijn, for his insightful comments on the paper and very useful suggestions. Roelof de Jong and Susan Kassin for discussions on these results. The authors would especially like to thank Lucas Macri for making his results available for comparison, prior to their publication.
This research has made use of the NASA/IPAC Extragalactic Database, which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration (NASA). This work is based on

observations with the NASA/ESA Hubble Space Telescope, obtained at the STScI, which is operated by the Association of Universities for Research in Astronomy (AURA), Inc., under NASA contract NAS5-26555. In addition, this publication makes use of the data products from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation. Support for this work was provided by NASA through grant number HST-AR-08360 from STScI. STScI is operated by AURA, Inc., under NASA contract NAS5-26555. We are also grateful for the financial support of the STScI Directors Discretionary Fund (grants 82206 and 82304 to R. J. Allen) and of the Kapteyn Astronomical Institute of Groningen University.

References

Alton, P. B., Bianchi, S., Rand, R. J., et al. 1998a, ApJ, 507, L125
Alton, P. B., Trewhella, M., Davies, J. I., et al. 1998b, A&A, 335, 807
Andredakis, Y. C., & van der Kruit, P. C. 1992, A&A, 265, 396
Beckman, J. E., Peletier, R. F., Knapen, J. H., Corradi, R. L. M., & Gentet, L. J. 1996, ApJ, 467, 175
Bell, E. F., & de Jong, R. S. 2001, ApJ, 550, 212
Block, D. L., Witt, A. N., Grosbol, P., Stockton, A., & Moneti, A. 1994, A&A, 288, 383
Davies, J. I., & Burstein, D., ed. 1995, The opacity of spiral disks
Davies, J. I., Alton, P., Trewhella, M., Evans, R., & Bianchi, S. 1999, MNRAS, 304, 495
de Jong, R. S. 1996, A&A, 313, 377
de Vaucouleurs, G., de Vaucouleurs, A., Corwin, H. G., et al. 1991, Third Reference Catalogue of Bright Galaxies, Volume 1–3, XII, 2069 pp. 7 figs.. (Berlin Heidelberg New York: Springer-Verlag)
Disney, M. 1990, Nature, 346, 105
Freedman, W. L., Madore, B. F., Gibson, B. K., et al. 2001, ApJ, 553, 47
Freeman, K. C. 1970, ApJ, 160, 811
Giovanelli, R., Haynes, M. P., Salzer, J. J., Costa, L. N., & Freudling, W. 1994, AJ, 107, 2036
Giovanelli, R., Haynes, M. P., Salzer, J. J., da Costa, L. N., & Freudling, W. 1995, AJ, 110, 1059
González, R. A., Allen, R. J., Dirsch, B., et al. 1998, ApJ, 506, 152
González, R. A., Loinard, L., Allen, R. J., & Muller, S. 2003, AJ, 125, 1182
Gonzalez-Serrano, J. I., & Valentijn, E. A. 1991, A&A, 242, 334
Graham, A. W. 2001, MNRAS, 326, 543
Hippelein, H., Haas, M., Tuffs, R. J., et al. 2003, A&A, 407, 137
Holmberg, E. 1958, Meddelanden fran Lunds Astronomiska Observatorium Serie II, 136, 1
Holwerda, B. W. 2005, Ph.D. Thesis, Kapteyn Astronomical Institute
Holwerda, B. W., Gonzalez, R. A., Allen, R. J., & van der Kruit, P. C. 2005a, AJ, 129, 1381
Holwerda, B. W., Gonzalez, R. A., Allen, R. J., & van der Kruit, P. C. 2005b, AJ, 129, 1396
Holwerda, B. W., Gonzalez, R. A., Allen, R. J., & van der Kruit, P. C. 2005c, A&A, 444, 319
Jarrett, T. H., Chester, T., Cutri, R., Schneider, S. E., & Huchra, J. P. 2003, AJ, 125, 525
Kassin, S. A., & de Jong, R. S. 2005, in prep.
Kleinmann, S. G., Lysaght, M. G., Pughe, W. L., et al. 1994, Experimental Astronomy, 3, 65
Macri, L. M., Huchra, J. P., Sakai, S., Mould, J. R., & Hughes, S. M. G. 2000, ApJS, 128, 461
Macri, L. M., Sakai, S., Mould, J. R., & Huchra, J. P. 2005, ApJS
Masters, K. L., Giovanelli, R., & Haynes, M. P. 2003, AJ, 126, 158
Nelson, A. E., Zaritsky, D., & Cutri, R. M. 1998, AJ, 115, 2273
Peletier, R. F., & Willner, S. P. 1992, AJ, 103, 1761
Popescu, C. C., Tuffs, R. J., Völk, H. J., Pierini, D., & Madore, B. F. 2002, ApJ, 567, 221
Radovich, M., Kahanpää, J., & Lemke, D. 2001, A&A, 377, 73
Stevens, J. A., Amure, M., & Gear, W. K. 2005, MNRAS, 357, 361
Trewhella, M., Davies, J. I., Alton, P. B., Bianchi, S., & Madore, B. F. 2000, ApJ, 543, 153
Tully, R. B., Pierce, M. J., Huang, J., et al. 1998, AJ, 115, 2264
Valentijn, E. A. 1990, Nature, 346, 153
Valentijn, E. A. 1994, MNRAS, 266, 614
White, R. E., & Keel, W. C. 1992, Nature, 359, 129
White, R. E., Keel, W. C., & Conselice, C. J. 2000, ApJ, 542, 761
Xilouris, E. M., Byun, Y. I., Kylafis, N. D., Paleologou, E. V., & Papamastorakis, J. 1999, A&A, 344, 868