AN INFRARED DETERMINATION OF THE REDDENING AND DISTANCE TO DWINGELOO 1

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ABSTRACT

We present the first published infrared observations of the nearby, highly obscured galaxy Dwingeloo 1 (Dw 1), including deep H-band imaging covering a total of 499 × 499, together with J and K_s imaging of the central 2′5 × 2′5. We used the small dispersion of the intrinsic infrared colors of spiral galaxies to determine an infrared H-band extinction of A_H = 0.47 ± 0.11 mag toward Dw 1. Using infrared colors reduces the uncertainties in the reddening and distance by a factor of 3. The H-band magnitude, corrected for extinction, and the infrared Tully-Fisher relation are then used to estimate a distance modulus of (m − M)_0 = 28.62 ± 0.27 and, thus, a distance of d = 5.3^{+0.7}_{−0.6} Mpc, which places Dw 1 at the far end of the IC 342/Maffei 1-2 group of galaxies. Our result is largely independent of the nature of the reddening law because we estimated both the reddening and the distance at the same wavelength range.

Key words: galaxies: individual (Dwingeloo 1) — galaxies: distances and redshifts — galaxies: photometry — infrared radiation

1. INTRODUCTION

Dwingeloo 1 (Dw 1) is a large SB_b/c galaxy, discovered both by Kraan-Korteweg et al. (1994) in a systematic H I emission survey of the northern part of the Milky Way made in search of obscured galaxies in the zone of avoidance and independently by Huchtmeier et al. (1995). Knowledge of the local mass distribution has implications for the peculiar velocity field, the direction and amplitude of the Local Group acceleration, the determination of parameters such as Ω_m and H_0, and the understanding of the formation and evolution of groups of galaxies (see, e.g., Peebles 1994; Marinoni et al. 1998). The discovery of this galaxy confirmed a long-standing suspicion that the tidal disruptions of Maffei 2 may be due to the presence of another massive galaxy nearby (see, e.g., Hurt et al. 1993).

Dw 1 lies in the direction of the IC 342/Maffei 1-2 group of galaxies, about 2′ away from Maffei 2. This corresponds to a physical separation of 175 kpc, assuming that Dw 1 and Maffei 2 are at a distance of 5 Mpc. Being the nearest barred spiral system, Dw 1 offers a unique opportunity to study the effect of the bar at high spatial resolution. The discoverers classified Dw 1 as an SBB or SBc galaxy (T = 4) and measured an angular diameter of 4′2. Later, McCall & Buta (1997), using deep optical I-band imaging, reclassified it as SB(s)cd with an angular diameter of 9′9 at μ_I = 25.0 mag arcsec^{-2}. Burton et al. (1996) extensively studied the neutral hydrogen content of Dw 1 and measured H I profile widths at the 20% and 50% levels of 201.2 ± 0.4 and 187.6 ± 0.6 km s^{-1}, respectively. The measured inclination of the gaseous disk was 51° ± 2° and the position angle 112°, with the major axis aligned with the bar.

Since the discovery of Dw 1, the determination of its distance has been hampered by the poorly known Galactic extinction. Optical VRI and Hz imaging, long-slit spectroscopy, and IRAS observations were summarized by Loan et al. (1996), who used a number of methods to estimate the foreground extinction toward Dw 1. The optical color excesses yielded A_V = 7.8 ± 3.0 mag, the measured Galactic H I column density A_V = 4.5 mag, and the 100 μm IRAS flux A_V = 3.2 mag. Finally, they applied optical I- and R-band Tully-Fisher relations to obtain distances ranging from 1.3 to 6.7 Mpc, with an average value of about 4 Mpc (assuming H_0 = 75 km s^{-1} Mpc^{-1}). Their main source of uncertainty was the value of the Galactic extinction. Phillipps & Davies (1997) challenged these extreme distance estimates on the basis of the very narrow span of central surface brightness in present-day spiral galaxies. Their best estimate for the extinction (A_H = 6 mag) places Dw 1 at a distance of 3.1–3.6 Mpc. These authors, by employing the diameter version of the Tully-Fisher relation (Persic, Salucci, & Stel 1996), obtained a distance of 2.7 Mpc.

The primary goal of the present study was to put stronger constraints on the foreground extinction and to obtain a better estimate of the distance to Dw 1. We chose to use infrared colors because of their small intrinsic variations among spiral galaxies (Aaronson 1977). In addition, the extinction in the H band is about 3 times smaller than in the I band and about 6 times smaller than in the V band (Rieke & Lebofsky 1985, hereafter RL85). Finally, for the distance we use the infrared Tully-Fisher (IRTF) relation, which shows a smaller intrinsic scatter than its optical counterpart (Aaronson, Huchra, & Mould 1979; Freedman 1990; Peletier & Willner 1993). The IRTF relation allows us to determine both the extinction and the distance at the same wavelength range, minimizing the errors arising from possible variations of the reddening law.

2. OBSERVATIONS AND DATA REDUCTION

We obtained JHK_s imaging of Dw 1 using a 256 × 256 NICMOS3 array at the 2.3 m Bok Telescope of the University of Arizona on Kitt Peak, with a plate scale of 0′6 pixel^{-1}, during a number of observing runs. We constructed a deep 499 × 499 H-band mosaic of Dw 1, whereas the J and K_s images covered only the central 2′5 × 2′5. Additional H-band imaging using a 1024 × 1024 array and plate scale of 0′5 pixel^{-1} was obtained at the same telescope on a subsequent observing run to calibrate the deep H-band imaging. The observational strategy consisted of taking galaxy images interleaved with sky images 6′–7′ away from Dw 1. Details of the observations are listed in Table 1.
TABLE 1

Log of Observations

| Detector | Filter | $t_{\text{exp}}$ (s) | Date       | Conditions       | Seeing (arcsec) |
|----------|--------|-----------------------|------------|------------------|-----------------|
| 256 × 256 | J      | 600                   | 1998 Nov 5 | Photometric      | 1.2             |
|          |        | 780                   | 1999 Jan 1 | Nonphotometric   | 1.5             |
|          | H      | 1800                  | 1998 Dec 30| Nonphotometric   | 1.1             |
|          | $K_s$  | 720                   | 1998 Nov 5 | Photometric      | 1.1             |
| 1024 × 1024 | H  | 760                   | 1999 Jan 6 | Photometric      | 1.0             |

The data reduction included subtraction of dark current frames, flat-fielding with median-combined empty sky frames, and sky subtraction. The mosaics were constructed by shifting the images to a common position with cubic spline interpolation. The photometric calibration was performed using observations of standard stars from the lists of Elias et al. (1982) and Hunt et al. (1998) when conditions were photometric. Conditions were nonphotometric for the

![Figure 1](image_url)

Fig. 1.—$H$-band mosaic of Dw 1 displayed on a logarithmic scale. The orientation is north up, east to the left. The field of view is 4.7 × 4.9. [See the electronic edition of the Journal for a color version of this figure.]
$H$-band mosaic, and this image was self-calibrated using the 1024 $\times$ 1024 data. In the next section, we use infrared colors of spiral galaxies to derive an estimate of the extinction to Dw 1. The colors for spiral galaxies were obtained with the $K$-band filter, whereas our measurements were taken with the $K_s$ (short-$K$) filter. Therefore it is necessary to determine what the difference is between the two filters. Very recently Persson et al. (1998) have obtained a new set of $JHK_s$ photometric standards. In their study, the average difference between the $K$ and $K_s$ magnitudes (for the red standards) is 0.0096 mag, with a standard deviation of 0.017 mag. We assume that using the $K_s$ filter instead of the $K$ filter introduces an extra uncertainty of $\pm 0.02$ mag in the photometric calibration of this filter. The errors associated with the photometric calibration are 0.05, 0.07, and 0.06 mag in $J$, $H$, and $K_s$, respectively.

In Figure 1, we display the $H$-band mosaic on a logarithmic scale. As can be seen from this figure, there are a large number of foreground stars that need to be removed before analyzing the data. The star removal from the $JHK_s$ images was done interactively. The affected pixels were then replaced with a linear surface fit to a circular annulus around each star. The automatic procedures failed largely because of point-spread function variations under non-photometric conditions. A bright star located southwest of the galaxy posed a major problem and was masked out throughout the data reduction. We assumed radial symmetry and replaced the region within about 90$''$ from the star with the data from the opposite side of the galaxy. We performed the photometry on the cleaned images, measuring the flux within elliptical isophotes with fixed position angle and ellipticity as determined from $H$-band observations (Burton et al. 1996).

3. DISCUSSION

3.1. Colors and Extinction

The surface brightness profiles in $JHK_s$ are given in Table 2 and displayed in Figure 2 along with the radial distribution of the $J-H$, $H-K_s$, and $J-K_s$ colors, and the total apparent magnitudes in $JHK_s$. In Table 2 and Figure 2, the 3$\sigma$ errors and the error bars represent the combined 3$\sigma$ variations from photon statistics, sky background variations, the elliptical isophotal fitting, and the photometric calibration. From the radial distribution of the colors, it is clear that the center of the galaxy appears slightly redder than the outer regions, as it does for the infrared colors of most spiral galaxies (Terndrup et al. 1994; de Jong 1996). Loan et al. (1996) report inverse optical color gradients in Dw 1; however, this may be the result of active star formation along the bar as found in some barred spirals (Shaw et al. 1995).

Before we tried to obtain an estimate of the extinction using the infrared colors, we fitted straight lines to assess the variation of the colors with increasing apertures:

$$H-K_s = 0.435 \pm 0.042 - (0.072 \pm 0.071)R,$$

$$J-H = 1.099 \pm 0.040 - (0.056 \pm 0.067)R,$$

$$J-K_s = 1.532 \pm 0.042 - (0.125 \pm 0.071)R,$$

where $R$ is the semimajor axis in arcminutes. These color gradients imply a change of 0.06–0.13 mag within the inner 2' of Dw 1, which may cause significant uncertainties in the reddening estimate. The smaller field of view of the $J$ and $K_s$ images prevents us from obtaining the total colors of Dw 1. However, the total flux in the $JHK_s$ bands is dominated by the inner 2' diameter region (see Fig. 2, bottom). Hence, we adopt the total observed colors at a radial distance of 1' from the center of the galaxy to be representative for the whole galaxy ($J-H = 1.04 \pm 0.10$, $J-K_s = 1.41 \pm 0.11$, and $H-K_s = 0.36 \pm 0.11$). To estimate the color excesses, we compared these colors with the mean integrated colors of SBb–SBcd galaxies: $J-H = 0.73 \pm 0.02$, $J-K_s = 0.94 \pm 0.03$, and $H-K_s = 0.21 \pm 0.02$ (Aaronson 1977). We have increased the errors in Aaronson’s colors to account for the uncertain Hubble type of Dw 1. The color excesses were converted into $H$-band ($A_H$), visual ($A_V$), and $B$-band ($A_B$) extinctions using RL85 and Mathis (1990, hereafter M90) extinction laws. The results are summarized in Table 3. Henceforth, we will use $A_H = 0.47 \pm 0.11$ mag from extinction law of M90 for the sake of compatibility with previous work. This value is close to the estimate based on the IRAS 100 $\mu$m flux (Loan et al. 1996).

Finally, we used the combined optical–near-infrared colors to verify our result. Loan et al. (1996) reported the following total apparent (not corrected for reddening) magnitudes for Dw 1: $m_l = 10.7 \pm 0.2$, $m_R = 12.2 \pm 0.2$, and $m_V = 14.0 \pm 0.5$. We measured a total $H$-band magnitude $m_H = 8.3 \pm 0.2$ and compared the observed colors with the intrinsic colors as determined by de Jong (1996): $I-H = 1.44 \pm 0.20$, $R-H = 2.01 \pm 0.20$, and $V-H = 2.50 \pm 0.20$. Mathis’s extinction law (M90) yields $A_H = 0.56 \pm 0.23, 0.58 \pm 0.12, and 0.47 \pm 0.11$ mag, respectively, in good agreement with our infrared estimates.

3.2. Tully-Fisher Distance to Dw 1

To determine the distance to Dw 1, we chose to apply the IRTF relation because of its lower intrinsic dispersion and
the reduced extinction in the $H$ band, with the additional advantage that the extinction and the distance are estimated at the same wavelength. The IRTF relation was pioneered by Aaronson et al. (1979). However, we chose to employ the IRTF relation calibrated by Freedman (1990), using local galaxies with Cepheid-based distances, and the relations of Peletier & Willner (1993), calibrated relative to the distance of the Ursa Major galaxy cluster.

Freedman’s (1990) calibration for the IRTF relation leads to the following expression: $H_{\text{abs}} = (-10.26 \pm 0.49) \log \Delta V_{20}(0) - 2.57 - (21.02 \pm 0.08)$, where $\Delta V_{20}(0)$ is the inclination-corrected 20% level $H$ velocity profile width in km s$^{-1}$, $H_{\text{abs}}$ is the absolute $H$-band magnitude within a circular aperture of diameter $A$, for which $\log (A/D_0) = -0.5$, and $D_0$ is the $B$-band isophotal diameter at $H_{\text{B}} = 25$ mag arcsec$^{-2}$. Using $\Delta V_{20}(0) = 259.0 \pm 0.5$ km s$^{-1}$, which is the corrected value of Burton et al.
(1996) for the inclination of the galaxy, the above expression predicts an absolute $H$-band magnitude $H^{\text{obs}}_{0.5} = -20.13 \pm 0.21$ mag.

Although $B$-band surface photometry for Dw 1 is not available, we can use the intrinsic integrated colors for Sb–Sc galaxies, $B - H = 3.28 \pm 0.14$ (de Jong 1996), to estimate $D_0$. The $\mu_B, \mu_g = 25$ mag arcsec$^{-2}$ isophote corresponds to an $H$-band surface brightness (corrected for extinction) of $\mu_H, \mu_g = 21.72 \pm 0.14$ mag arcsec$^{-2}$. Taking into account the $H$-band extinction, this is equivalent to an observed (not corrected for extinction) value of $\mu_H = 22.19 \pm 0.17$ mag arcsec$^{-2}$. As can be seen from Figure 2, this value exceeds the boundaries of the $H$-band mosaic. However, the surface brightness profile can be easily extrapolated. We fitted an exponential disk $[\mu_H \propto \exp(-r/r_d)]$, where $r$ is the semimajor axis and $r_d$ is the disk scale length to the surface brightness profile from a radial distance of 2\,' outward, where the bulge contribution in negligible, and estimated the value $D_0 = 8.5 \pm 0.8$. The apparent $H$-band magnitude (not corrected for extinction) for a circular aperture with diameter of $A_{0.5} = 2.7 \pm 0.2$ is then $m(H^{\text{app}}_{0.5}) = 8.96 \pm 0.12$ mag, which provides a distance modulus of $(m - M)_0 = 28.62 \pm 0.26$ and a distance of $d = 5.3 \pm 0.6$ Mpc.

The IRTF relation was initially calibrated for circular apertures because only single-pixel detectors were used at the time (Aaronson et al. 1979). Naturally, one would expect a transition to elliptical apertures to reduce the internal dispersion of the IRTF relation because they correct for the galaxy inclination. Peletier & Willner (1993) studied the problem in detail and reported no significant change in the calibration of the IRTF relation when elliptical apertures were used. A possible explanation is that the higher internal absorption, which increases with inclination, cancels out the projection effect. Peletier & Willner (1993) used elliptical apertures and obtained the following calibration for spiral galaxies in the Ursa Major galaxy cluster: $\log V_2(0) = -0.085[H^{\text{app}}_{0.5} + (m - M)_0 - 9.0] + 2.603$. We used a distance modulus to the Ursa Major Cluster of $(m - M)_0 = 30.95 \pm 0.17$ mag (Pierce & Tully 1988). This gives $H^{\text{obs}}_{0.5} = -19.72 \pm 0.52$ mag. However, we are still left with the problem of extrapolating the observed total luminosity profile out to $D_0$. The measured total (not corrected for extinction) $H$-band magnitude within an elliptical aperture with major axis $2.7 \pm 0.2$ and axial ratio 1.56 (Loan et al. 1996) is $m(H^{\text{app}}_{0.5}) = 9.19 \pm 0.43$. Correcting for the reddening, we obtained a distance modulus of $(m - M)_0 = 28.44 \pm 0.69$ mag and distance $d = 4.9 \pm 1.3$ Mpc. The intrinsic spread of the Peletier & Willner (1993) IRTF relation and the uncertain distance to the Ursa Major Cluster account for the increased errors of this estimate.

We can now use our reddening estimate to correct the optical $I$- and $R$-band photometry of Loan et al. (1996) and use the optical Tully-Fisher relations to obtain another distance estimate. The two reddening laws discussed in the preceding section predict the same $A_I / A_R$ ratio within a few percent. Adopting Mathis's extinction law (M90), we find $I$- and $B$-band extinctions of $A_I = 1.3 \pm 0.5$ mag and $A_R = 3.6 \pm 0.8$ mag, lower than the value $A_R = 4.3$ mag in Loan et al. (1996). This places Dw 1 at an average distance of $5.5 \pm 0.8$ Mpc.

These distance determinations place Dw 1 behind NGC 1560, at $3.5 \pm 0.7$ Mpc, behind UGC 105, at $3.8 \pm 0.9$ Mpc (Krismer, Tully, & Gioia 1995), and behind Maffei 1, at $4.2 \pm 0.5$ Mpc (Luppino & Toney 1993).

4. CONCLUSIONS

We have obtained deep near-infrared imaging of the highly obscured galaxy Dw 1. The observed infrared colors were used to obtain a very accurate estimate of the extinction in the $H$ band, $A_H = 0.47 \pm 0.11$ mag. This value was confirmed by the optical near-infrared color excesses and is close to the estimate based on the IRAS 10 $\mu$m flux (Loan et al. 1996). Our approach is more reliable than previous works in that we did not make any additional assumptions for the relation between $A_I$ and $H_1$, or for the IRAS 100 $\mu$m emission. In addition, the IRTF relation allowed us to estimate both the reddening and distance at the same wavelength range. This makes our results largely independent of the choice of the reddening law, with the additional advantage that the IRTF shows a smaller dispersion than its optical counterpart. Finally, the infrared reddening estimates are more reliable than those in the optical because infrared colors of spiral galaxies show a smaller intrinsic dispersion and are less sensitive to the history of star formation than are optical colors (Vazdekis et al. 1996).

The IRTF relation (Freedman 1990) yielded a distance of $d = 5.3 \pm 0.6$ Mpc, which places Dw 1 at the far end of the IC 342/Maffei 1-2 Group. We also confirmed that Dw 1 has an angular diameter greater than 7', larger than the originally measured value of 4.2.

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