THE EXTINCTION AND DISTANCE OF MAFFEI 2 AND A NEW VIEW OF THE IC 342/MAFFEI GROUP

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ABSTRACT

We have obtained spectra of H ii regions in the heavily obscured spiral galaxy Maffei 2. The observations have allowed for a determination of the Galactic extinction of this galaxy using a correlation between extinction and hydrogen column density observed among spiral galaxies. The technique reveals that the optical depth of Galactic dust at 1 μm obscuring Maffei 2 is τ1 = 2.017 ± 0.211, which implies that A_V = 5.58 ± 0.58 mag, significantly higher than observed for the giant elliptical Maffei 1 despite its similar latitude. For comparison, we apply the same technique to IC 342, a neighboring spiral to Maffei 2 but with more moderate obscuration by Galactic dust, owing to its higher Galactic latitude. For this galaxy, we obtain τ1 = 0.692 ± 0.066, which agrees within errors with the value of 0.639 ± 0.102 derived from the reddening estimate of Schlegel et al. (1998). We therefore adopt the weighted mean of τ1 = 0.677 ± 0.056 for the extinction of IC 342, which implies that A_V = 1.92 ± 0.16 mag. A new distance estimate for Maffei 2 of 3.34 ± 0.56 Mpc is obtained from a self-consistent Tully-Fisher relation in / adjusted to the NGC 4258 maser zero point. With our new measurement of M_V, Maffei 2 joins Maffei 1 and IC 342 as one of three giant members of the nearby IC 342/Maffei Group of galaxies. We present the revised properties of all three galaxies based on the most accurate extinction and distance estimates to date, accounting for shifts in the effective wavelengths of broadband filters as this effect can be significant for highly reddened galaxies. The revised distances are consistent with what would be suspected for the Hubble Flow, making it highly unlikely that the galaxies interacted with the Local Group since the big bang.

Subject headings: galaxies: clusters: individual (IC 342-Maffei) — galaxies: distances and redshifts — galaxies: individual (Maffei 1, Maffei 2, IC 342)

1. INTRODUCTION

The spiral galaxy Maffei 2 was first detected by Paolo Maffei in 1968 on a near-infrared Schmidt plate (Maffei 1968). Recent I-band photometry of this galaxy reveals a large highly inclined barred spiral of Hubble type Sbc with isophotes visible out to 12′ from the nucleus (Buta & McCall 1999). If the galaxy lies within 2–6 Mpc as suggested in previous studies (Bottinelli et al. 1971; Spinrad et al. 1973), it must be among the dominant galaxies in our Galactic neighborhood, which raises the question of its dynamical role in the early evolution of the Local Group. Unfortunately, a precise distance to Maffei 2 has remained elusive owing to the heavy obscuration by dust in the Milky Way disk associated with its low Galactic latitude (δ = −0.33°). Attempts to determine the Galactic extinction have so far produced ambiguous results: Spinrad et al. (1973) derived a value of A_V = 6.3 mag by comparing the nuclear spectrum with that of M31 and estimated that the galaxy suffers more extinction than the giant elliptical Maffei 1 by about 1 mag in V. However, a modern estimate of the reddening of Maffei 1 has been measured by Fingerhut et al. (2003, hereafter Paper 1) using a well-defined correlation between the Mg2 index and V − I color. They find A_V = 4.68 ± 0.18 mag, which is over 1.5 mag lower than the result reported by Spinrad et al. (1973). There is clearly a need to revisit the problem of the Galactic extinction of Maffei 2 before an attempt can be made to determine its distance.

In this study we derive the extragalactic extinction of Maffei 2 using a relationship among spiral galaxies between the extragalactic extinction of H ii regions and the column density of extragalactic hydrogen gas along the line of sight of the H ii regions. The correlation arises because the bulk of the extragalactic extinction of an H ii region is due to dust outside the region of emitting gas, where the extinguishing material is widely distributed and well mixed with hydrogen gas (McCall et al. 1985). A correlation between A_V and the annular-averaged column density of H i has been observed in both NGC 2403 (McCall 1984) and IC 342 (McCall 1989), substantiating the above claims. Using a sample of giant extragalactic H ii regions in late-type spiral galaxies, we construct the dust-gas relation and use it to determine the extragalactic extinction of two H ii regions in Maffei 2. By subtracting the extragalactic extinction from the total extinction of the H ii regions derived from their Balmer decrements, we obtain a measurement of the Galactic extinction. In deriving the Galactic extinction in various bandpasses, we account for shifts in the effective wavelengths of broadband filters, which can be significant for highly reddened galaxies (see McCall 2004). To check the validity of our result, we use the method applied to Maffei 2 to obtain the Galactic extinction of the nearby late-type spiral IC 342, for which an accurate independent estimate is available owing to its more moderate obscuration. Armed with the extinction to Maffei 2, we determine its distance using the Tully-Fisher relation constructed in V.

Our observations of H ii regions in Maffei 2 and IC 342 are presented in § 2, and reductions are outlined in § 3. In § 4 we describe the measurements of the total extinctions (Galactic plus
extragalactic) and the hydrogen column densities for the observed H II regions. In § 5 we construct the relation between dust and gas and use it to determine the Galactic extinction of Maffei 2 and IC 342. In § 6 we redetermine zero points for the extragalactic distance scale in a self-consistent fashion. We then derive the Tully-Fisher distance to Maffei 2, as well as a revised distance to IC 342 using recent observations of Cepheids by Saha et al. (2002). The revised properties of both galaxies in addition to Maffei 1 are presented in § 7, and the implications for the Local Group are discussed.

2. OBSERVATIONS

Long-slit spectroscopic observations of two H II regions in Maffei 2 were obtained on 1997 March 2 and 3 UT with the Ritchey-Chrétien spectrograph on the Mayall 4 m telescope at Kitt Peak National Observatory (KPNO). Observations were optimized to detect both Hα and Hβ emission to determine the extinction toward Maffei 2. The T2KB 2048 × 2048 CCD with 24 μm pixels was used in combination with the KPC10-A grating for wavelength coverage between 3500 and 7600 Å at 7 Å resolution. The spatial scale at the focal plane was 0.69″ pixel⁻¹. The slit was set to a width of 2″ and aligned in the north-south direction. The slit was placed over the southwest portion of Maffei 2 at the position of the brightest H II region (Spinrad et al. 1973; number 1a). Two individual clumps were also detected within a second H II region at the position of object number 2 in Spinrad et al. (1973). Two 1800 s exposures were taken on the night of March 2, and an additional three 1800 s exposures were obtained the following night. The effective air masses for the first and second night were 1.65 and 1.54, respectively.

Inspection of a single 1800 s dark frame showed that the total dark count rate was negligible compared to the sky. Internal and twilight flats were obtained to correct for variations over small and large spatial scales, respectively, on the CCD. HeNeAr arc lamp spectra were used for wavelength calibration. Flux calibrations were achieved by observing the standard stars Feige 67 and G191B2B (Oke 1990). Standard-star exposures were interspersed among object exposures over a range of air masses spanning those of Maffei 2.

In addition to the Maffei 2 observations, spectrophotometry of two H II regions in IC 342 was carried out to augment existing data for that galaxy. The spectra were acquired on 1992 January 28 UT with the 2.3 m f/9 Bok telescope and Boller & Chivens spectrograph at Steward Observatory. The detector was a Texas Instruments 800 × 800 CCD with 15 μm square pixels. Observations were made in first order with a 300 line mm⁻¹ grating blazed at 6690 Å. The grating was rotated to give coverage from 4300 to 7200 Å, over which the dispersion was 3.7 Å pixel⁻¹. The slit was opened up to 4.5″ to enable absolute calibration of line fluxes and to negate the possibility of errors in line ratios as a result of differential refraction. Precise pointing was guaranteed by rotating the slit to a position angle (21°) that admitted the light of a reference star only when the H II region was centered. A single 1800 s exposure was acquired, in which Hα and [N II] 6584 were clearly resolved. In order to minimize the effects of flexure on flat-fielding, a spectrum of an internal quartz lamp was acquired at the same location immediately following the target exposure. A helium-argon lamp was observed at a comparable position to calibrate the wavelength scale. A spectrum of twilight was acquired at the beginning of the night to map out the illumination pattern. To calibrate fluxes, the standard stars Hiltner 102, Feige 15, G191B2B, and HD 84937 were observed with the same wide slit as employed for the H II regions.

3. REDUCTIONS

The Maffei 2 spectra were reduced using standard IRAF⁵ routines. Reductions were carried out separately for each night. The object and flat-field frames were overseen corrected and bias corrected. The internal flat and sky flat frames were combined to produce a single internal flat frame and a single averaged sky flat frame. The averaged sky flat frame was corrected for pixel-to-pixel variations in response using a normalized internal flat frame. An illumination image was created from the processed sky flat to correct for the slit function. Then, each object frame was corrected by dividing the product of the illumination image and normalized internal flat. With two-dimensional fits to the arc spectra, geometric distortions were corrected so that the dispersion axis was made perpendicular to the spatial axis. Spectra of the two standard stars were combined to calibrate fluxes. Air-mass corrections were derived using a mean atmospheric extinction curve for KPNO. The five Maffei 2 spectral exposures were then aligned, shifted, and combined into a single spectral frame. The IC 342 spectra were reduced using standard IRAF routines in a similar manner as for the Maffei 2 spectra. Final one-dimensional flux-calibrated spectra were obtained via unweighted summed extractions.

Table 1 lists the observed flux ratios relative to H/β for the H II regions observed in Maffei 2 and IC 342.

4. MEASUREMENTS FOR MAFFEI 2 AND IC 342

4.1. Total Extinction

The extinction of a source is best quantified by its optical depth at some wavelength. Knowing optical depth, it is possible to evaluate the extinction in any filter by applying an appropriately scaled reddening law to the spectrum and integrating through the response function for the filter. The best choice of wavelength is 1 μm, as it falls in a part of the reddening law that is not very sensitive to environment and because the optical depth there is comparable numerically to E(B − V) (see McCaulley 2004).

The total extinction (Galactic plus extragalactic) of an H II region can be determined from the degree to which the observed Hα/ H/β ratio differs from the theoretical intrinsic ratio. The optical depth at 1 μm (τ1) can be computed from

\[ \tau_1 = \frac{2.5 \left[ \log \left( \frac{f_{\text{H}α}}{f_{\text{H}β}} \right) - \log \left( \frac{f_{\text{H}α}}{f_{\text{H}β}} \right) \right]}{R_{\text{H}α} - R_{\text{H}β}} \]

(1)

where \( f_{\text{H}α}/f_{\text{H}β} \) is the intrinsic Balmer ratio, \( f_{\text{H}α}/f_{\text{H}β} \) is the observed Balmer ratio corrected for underlying stellar absorption, and \( R_{\text{H}α} \) and \( R_{\text{H}β} \) are the reddening coefficients normalized to \( \tau_1 \) (i.e., \( R_1 = A_1/\tau_1 \), where \( A_1 \) is the extinction corresponding to \( \tau_1 \) at the wavelength \( \lambda \)). To estimate the reddening coefficients, we require a monochromatic extinction curve appropriate for the diffuse interstellar medium, which is primarily responsible for obscuring extragalactic sources. Fitzpatrick (1999) has developed an algorithm for determining the monochromatic reddening law associated with any particular value of the ratio of total to selective extinction, \( R_V = A_V/E(B − V) \). For the diffuse interstellar medium, \( R_V = 3.07 \pm 0.05 \) for a star of zero color in the limit of zero extinction (McCaulley 2004). The reddening law chosen to evaluate the reddening coefficients is that given by the algorithm of Fitzpatrick (1999), which, when applied to the

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⁵ IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Associated Universities for Research in Astronomy, Inc., under contract to the National Science Foundation.
spectrum of Vega, yields $R_V = 3.07$ after integrating the flux passed by response curves characterizing the $B$ and $V$ filters. The resulting Balmer coefficients are $R_{6563} = 2.185$ and $R_{4861} = 3.374$.

The intrinsic Balmer ratio $(f_{6563}/f_{4861})^\circ$ for each H II region was estimated from the emissivities of Storey & Hummer (1995). An initial approximation for $\tau_1$ was derived from equation (1) using $(f_{6563}/f_{4861})^\circ = 2.91$, which was computed by assuming a temperature of 8000 K and an electron density of 100 cm$^{-3}$, these being typical values for giant extragalactic H II regions (McCall et al. 1985). Then, the approximation for $\tau_1$ was used to correct [O II] $\lambda\lambda 3727$/H$\beta$ and [O III] $\lambda\lambda 5007$/H$\beta$ for reddening using reddening coefficients $R_{3727} = 4.379$ and $R_{5007} = 3.237$ computed in the same manner as for H$\alpha$ and H$\beta$. The corrected oxygen line ratios were used to estimate the oxygen abundance, log (O/H) = log [$n$(O)/$n$(H)], via the semiempirical calibration of S. S. McGaugh (1997, private communication). Next, log (O/H) was used to obtain an improved approximation of the H II region temperature using the theoretical correlations between electron temperature and oxygen abundance formulated by McGaugh (1991). The correlations are parameterized by the volume-averaged ionization parameter ($U$) and the upper mass limit for the ionizing stars. However, in the oxygen abundance range inhabited by the reference H II regions $[-3.9 < \log (O/H) < -2.8]$, the relations converge to straight lines of nearly identical slope with a spread of approximately ±600 K for intermediate values of $U$, which are typical of observed H II regions (McGaugh 1991). Thus, the temperature ($T$) in kelvin is given by

$$T = -7390 \log (O/H) - 17,433.$$  \hspace{1cm} (2)

Equation (2) was used to derive the next approximation of $(f_{6563}/f_{4861})^\circ$, which was then substituted back into equation (1) to obtain the next estimate of $\tau_1$. This process was iterated until $(f_{6563}/f_{4861})^\circ$, and thereby $\tau_1$, converged. Table 2 lists the observed and intrinsic fluxes, as well as the oxygen abundances, temperatures, and total extinctions, found for the H II regions in Maffei 2 and IC 342.

### Table 1: Measurements of H II Regions in Maffei 2 and IC 342

| Line                | Maffei 2       | IC 342       |
|---------------------|----------------|--------------|
|                    | [-0095, -0045]$^b$ | [-0091, -0065]$^b$ | [+0055, -0333]$^b$ | [+0072, -0292]$^b$ |
| H$\alpha$           | ...            | ...          | 27.0 ± 3.4      | ...          |
| H$\beta$            | 100 ± 28       | 100 ± 31     | 100 ± 5.2      | 100 ± 8.2    |
| [O II] $\lambda$4959| ...            | ...          | 29.7 ± 2.6     | 10.2 ± 3.7   |
| [O III] $\lambda$5007| ...        | ...          | 88.6 ± 3.2     | 19.2 ± 4.4   |
| He i $\lambda$5876  | ...            | ...          | 19.4 ± 3.1     | ...          |
| [O i] $\lambda$6300 | ...            | ...          | 18.8 ± 1.7     | ...          |
| [N ii] $\lambda$6548| 347 ± 165      | 474 ± 92     | 637 ± 34       | 668 ± 33     |
| H$\alpha$           | 4376 ± 201     | 5867 ± 113   | 195 ± 28       | 195 ± 27     |
| [N ii] $\lambda$6583| 1613 ± 172     | 1601 ± 94    | ...            | ...          |
| He i $\lambda$6678  | ...            | ...          | 11.8 ± 2.1     | ...          |
| [S ii] $\lambda$6716| 606 ± 39       | 719 ± 94     | 61.1 ± 2.3     | 71.4 ± 7.0   |
| [S ii] $\lambda$6731| 448 ± 37       | 565 ± 90     | 41.8 ± 2.2     | 45.5 ± 6.5   |
| [Ar iii] $\lambda$7136| ...         | ...          | 38.4 ± 2.5     | ...          |
| $f_{6563}$ (10$^{-16}$ ergs s$^{-1}$ cm$^{-2}$) | 1.09 ± 0.30 | 1.06 ± 0.33 | 45.1 ± 2.4 | 224 ± 1.8 |
| $W_{6563}$ ($\AA$) | 16.5 ± 5.2    | 6.6 ± 2.1    | 442 ± 224      | 112 ± 22     |

$^a$ Uncorrected line flux relative to H$\beta$ scaled to H$\beta$. The errors in the line ratios do not include the error in $f_{6563}$.

$^b$ Eastward and northward offset of the H II region from the galaxy nucleus as projected on the sky, in arcseconds.

$^c$ Equivalent width of H$\beta$ emission. (For typical H II regions, the equivalent width of H$\beta$ emission is so strong that the correction to the H$\beta$ flux is negligible.)

#### 4.2. Hydrogen Column Densities

The surface brightnesses of H i 21 cm and CO 2.6 mm line radiation are traced by atomic and molecular hydrogen gas, respectively, which is distributed all the way from the far side to the near side of a galaxy. In the Milky Way, the scale heights of the H i and H$_2$ gas are ~150 and ~60 pc, respectively (Malhotra 1994, 1995). The H II regions, being associated with the young stellar population, are confined to a layer with a scale height of only ~90 pc (van der Kruit 1986). The column density of extragalactic gas in the foreground of an H II region can therefore be approximated as half the column density of hydrogen derived from observations of H i and CO along the line of sight, with some scatter caused by deviations in position from the exact mid-plane and by concentrations of dust in the immediate vicinity of the H II region. Thus, the hydrogen column density $n_{H}$ in atoms cm$^{-2}$ along the line of sight is given by

$$n_{H} = N_{H}/2 = (N_{H_i} + 2N_{H_2})/2,$$  \hspace{1cm} (3)

where $N_{H_i}$ and $N_{H_2}$ are the column densities of H i and H$_2$, respectively. The $N_{H_2}$ term is doubled to preserve the proportionality between the number of dust particles and hydrogen atoms.

The annular-averaged column densities of H i at the deprojected radii of the two H II regions in Maffei 2 were measured from the H i radial profile of Hurt et al. (1996). The CO ($J = 1-0$) intensities at the locations of the H II regions were obtained from the radial profile provided by A. M. Mason & C. D. Wilson (2003, private communication; see also Mason & Wilson 2004). For IC 342, the H i column densities and CO intensities at the locations of the H II regions were measured from the radial profiles of Newton (1980b) and Crosthwaite et al. (2001), respectively.

The conversion from CO intensity ($I_{CO}$) to H$_2$ column density was found to have a metallicity dependence in independent studies by Wilson (1995) and Arimoto et al. (1996). The conversion relation adopted here is from the former source, in which
| H ii Region   | r (arcsec) | \(W_{\text{H}{\beta}}\) (Å) | \(f_{\text{H}{\beta}}/f_{\text{H}{\alpha}}\) | \(T\) (K) | \(X_1\) (10²⁰ cm⁻²) (7) | \(\tau_1^{\text{em}}\) | \(N_{\text{H}{\alpha}}\) (10²⁰ cm⁻²) (9) | \(n_{\text{H}}\) (10²⁰ cm⁻²) (11) | \(\tau_1^{\text{opt}}\) (13) | References |
|--------------|------------|----------------------------|---------------------------------|--------|---------------------------|-----------------|---------------------------------|---------------------------|---------------------|-------------|
| Maffei 2     | –0091, –0065 | 168 | 6.6 | 45.62 ± 0.14 | –2.98a | 4572 | 3.07 | 2.46 ± 0.30 | 18.13 ± 2.42 | 2.24 | 29.12 ± 8.08 | 38.19 ± 8.17 | 0.38 ± 0.09 | FL07 |
| –0095, –0045 | 187        | 16.5 | 39.25 ± 0.13 | –3.00a | 4748 | 3.06 | 2.33 ± 0.27 | 18.90 ± 2.64 | 2.33 | 26.34 ± 7.29 | 35.79 ± 7.41 | 0.37 ± 0.08 | FL07 |
| IC 342       | –0521, –0166 | 564 | 197.0 | 10.54 ± 0.04 | –3.76 | 10330 | 2.86 | 1.19 ± 0.09 | 9.33 ± 1.72 | 7.61 | 0.00 ± 0.00 | 4.66 ± 0.86 | 0.19 ± 0.07 | MR85 |
| –0077, –0288 | 303        | 64.3 | 7.64 ± 0.04 | –3.01 | 4835 | 3.05 | 0.84 ± 0.09 | 8.20 ± 1.10 | 2.37 | 7.34 ± 2.02 | 11.44 ± 2.10 | 0.23 ± 0.16 | MR85 |
| +0832, –0158 | 916 | 53.9 | 6.46 ± 0.04 | –3.76 | 10390 | 2.86 | 0.74 ± 0.09 | 7.30 ± 1.83 | 7.71 | 0.00 ± 0.00 | 3.65 ± 0.91 | 0.18 ± 0.08 | MR85 |
| –0150, –0031 | 160        | 7.68 ± 0.05 | –3.24a | 6527 | 2.97 | 0.87 ± 0.10 | 4.31 ± 0.46 | 3.40 | 23.15 ± 6.28 | 25.31 ± 6.28 | 0.31 ± 0.48 | BK82 |
| +0055, –0333 | 357 | 44.24 | 6.34 ± 0.05 | –3.33a | 7147 | 2.94 | 0.70 ± 0.11 | 8.69 ± 1.26 | 3.87 | 6.37 ± 1.72 | 10.71 ± 1.83 | 0.22 ± 0.14 | FL07 |
| +0072, –0292 | 321 | 112.0 | 6.57 ± 0.06 | –3.31a | 7032 | 2.95 | 0.73 ± 0.13 | 8.36 ± 1.15 | 3.78 | 8.52 ± 2.30 | 12.70 ± 2.38 | 0.24 ± 0.18 | FL07 |

**Notes.**—Col. (1): Eastward and northward offset of the H ii region from the galaxy nucleus as projected on the sky, in arcseconds. Col. (2): Deprojected galactocentric radius of the H ii region using \(i\) and \(\phi\) from Table 3. Col. (3): Equivalent width of the H\(\beta\) emission line, where available. Col. (4): Observed H\(\alpha\)/H\(\beta\) flux ratio, corrected for underlying stellar absorption but not for Galactic reddening, assuming an equivalent width for absorption of 1.9 Å (see McCall et al. 1985). Col. (5): Oxygen abundance of the H ii region derived from the forbidden oxygen lines (see \(\frac{4.1}{3}\)). Col. (6): Equilibrium temperature of the H ii region derived from \(\log (O/\text{H})\) (see \(\frac{4.1}{3}\)). Col. (7): Intrinsic Balmer flux ratio based on the H ii region’s equilibrium temperature and an electron density of 100 cm⁻³. Col. (8): Total optical depth at 1 \(\mu\)m of the H ii region derived from the observed and intrinsic Balmer decrements (eq. [1]). Col. (9): Annular averaged column density of neutral hydrogen within the annulus at \(r\). Col. (10): Conversion factor for CO intensity to \(H_2\) column density (\(X = N_{\text{H}_2}/L_{\text{CO}}\)). Col. (11): Annular averaged column density of molecular hydrogen within the annulus at \(r\). Col. (12): Half of the column density of hydrogen in both atomic and molecular form at \(r\). Col. (13): Extragalactic optical depth at 1 \(\mu\)m of the H ii region, i.e., the difference between the total optical depth \(\tau_1^{\text{em}}\) and the Galactic optical depth \(\tau_1^{\text{gal}}\). For Maffei 2 and IC 342, \(\tau_1^{\text{opt}}\) is computed from eq. (6). Col. (14): Source of the H ii region spectrum. Abbreviations are cross-referenced in the bibliography.

\*a Indicates the absence of oxygen line data, resulting in the use of eq. (4) or eq. (5) to determine the temperature, and hence \(\log (O/\text{H})\).

**References.**—(BK82) Blair et al. 1982; (FL07) This study; (MR85) McCall et al. 1985.
measurements of $X = N_{\text{H}_2}/I_{\text{CO}}$ and log (O/H) are determined in a homogeneous manner by applying the virial theorem to individual molecular clouds in nearby spiral and dwarf irregular galaxies. For each H ii region, the conversion factor ($X$) along with the H i and H2 column densities are summarized in Table 2.

### 5. EXTINCTION

#### 5.1. The Relationship between Dust and Gas

We have constructed the relationship between extragalactic extinction and hydrogen column density for a sample of 74 reference H ii regions in 10 spiral galaxies of type Sbc and Scd. We have restricted our sample to galaxies for which (1) the Galactic extinction is small and thus well known [i.e., $E(B-V) < 0.05$ mag], (2) the radial profile of H i has been determined from aperture synthesis maps, and (3) there is a published radial profile of the CO ($J = 1-0$) line. We have further required that the constituent H ii regions be nonnuclear to ensure the reliability of abundance calibrations, where “nonnuclear” is defined here as having a radius greater than 15% of the host galaxy’s disk scale length. In addition, we have rejected any H ii region located beyond the radial boundaries of the H i maps. Lastly, all H ii regions were required to have measurements of the flux at Hα and Hβ and the equivalent width of the Hβ emission line in order to account for the depression of Balmer emission by underlying Balmer absorption from stars (for typical H ii regions, the equivalent width of Hα emission is so strong that the correction to the Hα flux is negligible). The galaxies meeting the above criteria are listed in Table 3.

The total extinctions of the reference H ii regions were derived in a manner consistent with those employed for Maffei 2 and IC 342 (see § 4.1). Several of the H ii regions were missing measurements for the oxygen line fluxes as a consequence of poor signal-to-noise ratio. Their temperatures were determined from a correlation between temperature and galactocentric radius found for the H ii regions for which oxygen line fluxes were available. As can be seen in Figure 1, the slope and intercept of the correlation appear to have a dependence on spiral morphology in the sense that H ii regions in late-type spiral galaxies have higher temperatures. We therefore adopt two linear fits: one for the spiral galaxies of type Sbc and one for those of type Scd. The fits are described by

$$T_{\text{Sbc}} = (1109 \pm 137)r/r_0 + (3004 \pm 266),$$

$$T_{\text{Scd}} = (656 \pm 171)r/r_0 + (6026 \pm 367),$$

where $T$ is in kelvin and $r/r_0$ is the deprojected galactocentric distance of the H ii region normalized to the host galaxy’s disk scale length. The rms deviations for the Sbc and Scd samples are 562 and 934 K, respectively.

![Figure 1](image_url)

Figure 1.—Correlation between H ii region temperature ($T$) and galactocentric radius normalized to the disk scale length ($r/r_0$) for H ii regions in the Sbc galaxy sample (filled circles) and the Scd galaxy sample (open circles). The rms deviation in temperature is 562 K for the Sbc sample and 934 K for the Scd sample. The linear fits represented by the solid lines are given by eqs. (4) and (5).
| H II Region       | References | \( r \) (arcsec) | \( W_{H\alpha} \) (Å) | \( f_{H\alpha}/f_{H\beta} \) | \( \log (O/H) \) | \( T \) (K) | \( f_{H\alpha} (f_{H\beta}) \) | \( \tau_{5000} \) | \( N_{H_1} \) (10\(^20\) cm\(^{-2}\)) | \( X \) (10\(^{20}\) cm\(^{-2}\) (km s\(^{-1}\))\(^{-1}\)) | \( N_{H_2} \) (10\(^{20}\) cm\(^{-2}\)) | \( m_1 \) (10\(^{20}\) cm\(^{-2}\)) | \( ^{13}\)C(\(^{12}\)C) | References |
|------------------|------------|------------------|---------------------|---------------------|-----------------|-----------|---------------------|----------------|-------------------------------|-------------------------------|---------------------|------------------|------------------|------------------|
| NGC 2903         | MR85       | 53               | 30.8               | 3.99                | -2.88            | 3877      | 3.13                | 0.22            | 14.26                         | 1.94                          | 11.92              | 38.10            | 0.19             |
| NGC 4303         | SS91       | 45               | 33.0               | 3.84                | -2.93            | 4255      | 3.10                | 0.20            | 11.67                         | 2.10                          | 19.97              | 51.61            | 0.16             |
| NGC 4321         | SS91       | 51               | 160.0              | 5.18                | -2.98            | 4569      | 3.07                | 0.48            | 11.36                         | 2.24                          | 17.49              | 46.34            | 0.44             |
| NGC 5055         | MR85       | 96               | 16.3               | 5.06                | -2.92            | 4164      | 3.11                | 0.45            | 15.53                         | 2.06                          | 9.95               | 35.43            | 0.41             |
| Region | Reference |
|--------|-----------|
| NGC 5194 | |
| [-0007, +0061] | 61 50.4 4.79 −2.89 3913 3.13 0.39 5.07 1.95 37.59 80.25 0.35 MR85 |
| [-0087, −0082] | 125 51.9 3.84 −2.90 3996 3.12 0.19 4.87 1.99 9.32 23.51 0.15 MR85 |
| NGC 598 | |
| [-0606, −1708] | 1,816 4.3 2.67 −3.20 6184 2.98 −0.10 9.42 3.16 0.00 9.42 −0.15 MR85 |
| [-0499, −0054] | 846 20.5 3.95 −3.24 6518 2.97 0.26 18.01 3.39 0.00 18.01 0.21 MR85 |
| [-0185, +0163] | 435 203.0 4.23 −3.28 6773 2.96 0.33 19.03 3.58 0.00 19.03 0.28 MR85 |
| [+0034, −0037] | 86 28.7 4.05 −3.14 5739 3.01 0.27 14.93 2.87 7.56 30.05 0.22 MR85 |
| [+0140, −0042] | 268 ... 4.84 −3.27 6752 2.96 0.45 15.61 3.56 0.00 15.61 0.40 KA81 |
| [+0140, +0340] | 368 117.0 3.49 −3.17 5998 2.99 0.14 16.09 3.04 0.00 16.09 0.09 VP88 |
| −0210, +0123 | 444 ... 4.76 −3.37 7488 2.93 0.44 19.48 4.16 0.00 19.48 0.40 KA81 |
| +0308, −0332 | 615 107.0 2.98 −3.21 6292 2.98 0.00 18.26 3.23 0.00 18.26 −0.05 VP88 |
| +0139, +0736 | 782 ... 4.31 −3.55 8814 2.89 0.36 15.19 5.52 0.00 15.19 0.32 KA81 |
| +0540, +0458 | 871 86.0 3.78 −3.33 7190 2.94 0.23 20.21 3.91 0.00 20.21 0.18 VP88 |
| −0520, +0345 | 1,129 20.0 2.84 −3.42 7830 2.92 −0.02 19.87 4.48 0.00 19.87 −0.07 VP88 |
| +0526, +1245 | 1,352 ... 3.07 −3.39 7642 2.92 0.04 17.83 4.30 0.00 17.83 0.00 KA81 |
| −0514, +0104 | 1,473 ... 4.48 −3.63 9425 2.88 0.40 19.87 6.28 0.00 19.87 0.36 KA81 |
| −0857, −0039 | 1,476 97.0 3.20 −3.46 8163 2.91 0.09 19.93 4.80 0.00 19.93 0.04 VP88 |
| −0454, +1029 | 1,675 ... 4.48 −3.61 9245 2.88 0.40 15.22 6.04 0.00 15.22 0.35 KA81 |
| NGC 2403 | |
| −0494, +0137 | 592 157.0 3.49 −3.55 8797 2.89 0.17 11.05 5.50 0.02 11.09 0.13 MR85 |
| −0133, −0146 | 393 155.9 3.40 −3.43 7906 2.92 0.14 15.67 4.55 0.09 15.85 0.09 MR85 |
| +0010, +0052 | 65 83.1 3.76 −3.27 6747 2.96 0.22 20.30 3.56 1.55 23.40 0.17 MR85 |
| +0045, +0069 | 165 180.5 4.26 −3.40 7678 2.92 0.34 21.17 4.33 0.56 22.29 0.30 MR85 |
| +0063, −0049 | 80 72.0 4.06 −3.16 5938 3.00 0.28 20.24 3.00 0.96 22.16 0.23 MR85 |
| +0165, +0136 | 416 213.0 3.60 −3.59 9087 2.89 0.20 15.07 5.84 0.09 15.25 0.16 MR85 |
| NGC 5457 | |
| −0376, −0063 | 390 61.9 3.40 −3.30 6954 2.95 0.13 8.63 3.71 1.08 10.79 0.12 MR85 |
| −0243, +0163 | 308 169.3 4.52 −3.40 7686 2.92 0.40 9.96 4.34 2.55 15.06 0.39 MR85 |
| +0098, +0272 | 291 68.2 3.42 −3.32 7088 2.95 0.14 10.17 3.82 2.60 15.37 0.13 MR85 |
| +0223, −0127 | 269 234.3 3.12 −3.28 6807 2.96 0.05 10.08 3.60 2.93 15.94 0.04 MR85 |
| +0252, −0010 | 287 249.4 4.51 −3.56 8879 2.89 0.40 10.22 5.59 3.93 18.08 0.39 MR85 |
| +0666, +0172 | 701 213.6 3.35 −3.67 9658 2.87 0.14 5.91 6.60 0.13 6.17 0.13 MR85 |
| +0167, +0123 | 172 162.2 4.14 −3.29 6918 2.95 0.18 8.33 3.69 6.91 22.15 0.30 RP82 |
| −0068, −0090 | 113 ... 4.84 −3.25 6611 2.97 0.45 7.34 10.74 28.82 0.44 RP82 |
| +0145, −0140 | 212 ... 4.41 −3.32 7124 2.94 0.37 9.68 3.85 5.14 19.96 0.36 RP82 |
| +0669, +0174 | 704 173.8 3.84 −3.67 9676 2.87 0.26 5.86 6.62 0.13 6.12 0.25 RP82 |
| +0250, −0113 | 288 195.0 5.03 −3.38 7517 2.93 0.49 10.21 4.19 2.92 16.05 0.48 RP82 |
| H II Region          | $r$  | $W_{H\beta}$ | $f_{H\alpha}/f_{H\beta}$ | log (O/H) | $T$  | $(f_{H\alpha}/f_{H\beta})_c$ | $r_{H\alpha}$ | $N_{H\alpha}$ | $X$  | $n_{H_2}$ | $n_{H_1}$ | References  |
|---------------------|------|--------------|--------------------------|-----------|------|----------------------------|---------------|---------------|------|------------|------------|-------------|
| [−0068, +0033]      | 78   | 83.0         | 4.14                     | −3.28     | 6800 | 2.96                       | 0.31          | 20.00         | 3.60 | 4.09       | 28.18      | SK96        |
| [−0054, −0056]      | 106  | 100.0        | 3.08                     | −3.31     | 7054 | 2.95                       | 0.04          | 12.68         | 3.80 | 1.47       | 15.62      | SK96        |
| [−0055, +0051]      | 75   | 127.0        | 3.57                     | −3.36     | 7364 | 2.93                       | 0.18          | 19.72         | 4.06 | 5.12       | 29.96      | SK96        |
| [−0042, +0035]      | 55   | 59.0         | 3.57                     | −3.11     | 5554 | 3.01                       | 0.15          | 17.71         | 2.76 | 7.27       | 32.25      | SK96        |
| [+0015, −0029]      | 37   | 280.0        | 3.54                     | −3.07     | 5222 | 3.03                       | 0.14          | 14.19         | 2.58 | 11.47      | 37.13      | SK96        |
| [−0019, +0013]      | 23   | 15.0         | 4.14                     | −3.23     | 6408 | 2.97                       | 0.30          | 13.08         | 3.31 | 19.14      | 51.36      | SK96        |

Note.—See Table 2 for column descriptions.

* Indicates the absence of oxygen line data, resulting in the use of eq. (4) or eq. (5) to determine the temperature and hence log (O/H).

References.—(KA81) Kwitter & Aller 1981; (MR85) McCall et al. 1985; (RP82) Rayo et al. 1982; (SK96) Skillman et al. 1996; (SS91) Shields & Skillman 1991; (VP88) Vilchez et al. 1988.
The extragalactic extinction of each H ii region (quantified by \( \tau_1^{\text{loc}} \)) was extracted from the total extinction (\( \tau_1^{\text{tot}} \)) observed in the Balmer decrement (eq. [1]) by subtracting the galactic extinction (\( \tau_1^{\text{gal}} \)) derived from the Galactic reddenings of Schlegel et al. (1998, hereafter SFD98). For each host galaxy, we computed \( \tau_1^{\text{gal}} \) from \( E(B-V) \) using the iterative process outlined in McCall (2004). Briefly, the integrated spectral energy distribution (SED) of a typical unreddened elliptical galaxy was extinguished by successive approximations of \( \tau_1^{\text{gal}} \) with the aid of the scaled monochromatic reddening law described in § 4.1. The application of this process was greatly facilitated by the York Extinction Solver (YES). The total gas column density (\( n_\text{H} \)) at the location of each reference H ii region was determined according to the procedure outlined in § 4.2. The gas column densities and extinctions of the H ii regions are provided in Table 4 along with the sources of the H i and CO data. The correlation between \( \tau_1^{\text{loc}} \) and \( n_\text{H} \) is shown in Figure 2 and does not appear to depend on spiral morphology within the range Sbc to Sd. We have therefore adopted the following least-squares fit to the entire reference data set:

\[
\tau_1^{\text{loc}} = (0.0057 \pm 0.0029)n_\text{H} + (0.163 \pm 0.041),
\]

where \( n_\text{H} \) is in units of \( 10^{20} \text{ cm}^{-2} \). The rms deviation in \( \tau_1^{\text{loc}} \) is 0.17.

Equation (6) improves on the dust-gas relation found previously by McCall (1989) by expanding the H ii region sample to include recent observations, by excluding NGC 6946 due to its high Galactic extinction, and by including H2 in the gas diagnostic. This last step has reduced the scatter considerably.

### 5.2. Uncertainties in the Dust-Gas Relation

The error in an estimate of \( \tau_1^{\text{loc}} \) for an H ii region from equation (6) can be computed from

\[
(\delta \tau_1^{\text{loc}})^2 = (m \delta n_\text{H})^2 + [\delta m(n_\text{H} - \langle n_\text{H} \rangle)]^2 + \sigma_n^2/n,
\]

where \( \delta n_\text{H} \) is the standard error associated with \( n_\text{H} \), \( m \) is the slope of the dust-gas correlation (eq. [6]), \( \delta m \) is the measurement error associated with the estimate of \( n_\text{H} \) for the H ii region, \( \sigma_n \) is the rms deviation of 0.17 in \( \tau_1^{\text{loc}} \) of the \( n = 74 \) reference data points about the linear fit, and \( \langle n_\text{H} \rangle \) is the mean \( n_\text{H} \) for the H ii region sample, found to be 12.50 \( \times 10^{20} \text{ cm}^{-2} \).

The measurement uncertainty in \( n_\text{H} \) for each reference H ii region was computed from one-half of the quadrature sum of the errors in \( N_{\text{H}1} \) and \( 2N_{\text{H}1} \). The greatest source of uncertainty in a measurement of \( n_\text{H} \) arises from taking the annular average of intensity measurements at a given radius. The uncertainty increases with distance from the nucleus; the larger the circumference of an annulus, the larger the area of galaxy contained within the annulus, and therefore the greater the possibility of intensity fluctuations. We have derived an expression for this uncertainty by examining the reference galaxies for which measurements of H i were supplied separately for each half of the disk. For a given annulus, the difference between the column densities within each semianulus (\( \Delta N_\text{H1i} \)) relative to the mean (\( \langle N_{\text{H1i}} \rangle \)) is found to be a linear function of the fractional galactocentric radius \( r/r_0 \), with an rms deviation of 0.16. The uncertainty in a measurement of \( N_{\text{H1i}} \) from an annular-averaged radial distribution can therefore be estimated from

\[
\Delta N_{\text{H1i}}/\langle N_{\text{H1i}} \rangle = 0.04r/r_0 + 0.08.
\]

Adopting this approach, the average error in \( N_{\text{H1i}} \) for the reference H ii regions is 15%.

The dominant contributions to the uncertainty in \( N_{\text{H1i}} \) for each reference H ii region are the measurement uncertainty in \( I_{\text{CO}} \), for which we find a mean value of 26%, and the uncertainty in the CO-to-H2 conversion factor (X). The latter source is dominated by the scatter of 1.03 \( \times 10^{20} \text{ cm}^{-2} \) (K km s\(^{-1}\))\(^{-1}\) in the adopted metallicity relation (see § 4.2) and the measurement uncertainty in the oxygen abundance, for which we adopt 0.2 dex as recommended by McGaugh (1991). Taking the above sources into account, we find a mean measurement uncertainty in \( n_\text{H} \) of 19% for the reference H ii regions. We note that the mean measurement uncertainty in \( n_\text{H} \) for the Sbc galaxies exceeds that found for the Sd galaxies by 6%, as a result of the considerably larger uncertainties in \( N_{\text{H1i}} \). This is likely due to the higher H2 content in the Sbc galaxies, as nearly 40% of the Sd H ii regions are found in regions of negligible CO.

The measurement uncertainty in \( \tau_1^{\text{loc}} \) for each H ii region is simply the quadrature sum of the uncertainties associated with \( \tau_1^{\text{tot}} \) and \( \tau_1^{\text{gal}} \). The uncertainty in \( \tau_1^{\text{tot}} \) is dominated by the measurement error in the observed H\( \alpha/H\beta \) flux, given the weak dependence of the intrinsic Balmer ratio on temperature. [The mean error in \( f_{\text{H}\alpha}/f_{\text{H}\beta} \) owing to the temperature estimate was found to be under 2% and was therefore considered negligible.] The mean measurement error in \( f_{\text{H}\alpha}/f_{\text{H}\beta} \) is 11%, which was computed from the quadrature sum of the signal-to-noise ratio error in the flux and a 10% error arising from the uncertainty in the overall response correction (McCall 1982, p. 103). The contributions from the uncertainties in the reddening coefficients referenced in the text, which are contained in a table in the York Extinction Solver (YES). The York Extinction Solver is a Web-based application developed by the Department of Physics and Astronomy at York University and hosted by the Canadian Astronomy Data Centre (CADC). It can be accessed at http://cadcwww.hia.nrc.ca/yes.
were found to be negligible. Adopting a 0.16 fractional error in $\tau_{\text{gal}}^{\text{tot}}$ as recommended by SFD98, the mean measurement uncertainty in $\tau_{\text{loc}}^{\text{tot}}$ for the reference H II regions is 0.10. Thus, the scatter of 0.17 in the dust-gas relation may be mostly due to the measurement uncertainties. The scatter above that associated with the measurement errors may be arising from dust concentrated near the H II regions, which is not traced by $n_0$. The nonzero intercept proves the existence of such localized dust. However, the fact that this scatter does not swamp the dust-gas trend implies that the extinction due to this dust is roughly constant among H II regions. A value of $\tau_{\text{loc}}^{\text{tot}}$ obtained from equation (6) therefore includes both the optical depth due to widespread dust in the extragalactic foreground and the average optical depth due to dust associated with the star formation regions.

5.3. The Galactic Extinction of Maffei 2 and IC 342

The derived extragalactic extinctions for the H II regions in Maffei 2 and IC 342 are given in Table 2. The quoted errors were derived in the same manner as for the reference H II regions (see § 5.2). We find mean total extinctions of $\tau_{\text{gal}}^{\text{tot}} = 2.390 \pm 0.203$ for Maffei 2 and $\tau_{\text{gal}}^{\text{tot}} = 0.866 \pm 0.041$ for IC 342. Madore & Freedman (1992) estimated the total reddening of hot stars in IC 342 from a comparison of the $B - V$ color of the blue “plume” in the color-magnitude diagram with that of IC 1613. They obtained $E(B - V) = 0.79 \pm 0.05$ mag, corresponding to $\tau_{\text{gal}}^{\text{tot}} = 0.82 \pm 0.05$ based on the SED of a B0 V star. Their result is consistent within errors with the mean total extinction found for H II regions in IC 342.

In Figure 2, the total extinctions for the heavily obscured H II regions are plotted over the dust-gas correlation found for the reference H II regions. The weighted mean of the extinction offsets of the heavily obscured H II regions implies Galactic extinctions of $\tau_{\text{gal}}^{\text{tot}} = 2.017 \pm 0.211$ for Maffei 2 and $\tau_{\text{gal}}^{\text{tot}} = 0.692 \pm 0.066$ for IC 342.

The SFD98 reddening for IC 342 is $E(B - V) = 0.558 \pm 0.069$ mag, which corresponds to a Galactic optical depth of $\tau_{\text{gal}}^{\text{tot}} = 0.639 \pm 0.102$ according to the treatment outlined in § 5.1. This value is consistent with our estimate of $0.692 \pm 0.066$ within errors, which validates our extinction analysis in general, as well as the extinction estimate for Maffei 2 in particular. While SFD98 caution against the use of their reddening maps for objects within $\pm 5^\circ$ of the Galactic plane, the Galactic latitude of IC 342 is safely outside this range at $b = 10.58^\circ$. We therefore have no reason to reject the SFD98 value of $\tau_{\text{gal}}^{\text{tot}}$ for this galaxy, so we adopt the weighted mean of both values, which yields $\tau_{\text{gal}}^{\text{tot}} = 0.677 \pm 0.056$.

The extinction parameters and corrected magnitudes of Maffei 2 and IC 342 are given in Table 6 below. The lower values of the reddening coefficients $A_{V}/A_{I}$ observed for Maffei 2 for each broadband filter $\Lambda$ are due to shifts in the effective wavelengths of $\Lambda$ toward the red caused by the higher Galactic extinction and inclination.

6. DISTANCES

6.1. Zero Points of the Extragalactic Distance Scale

As explained in §§ 4.1 and 5.1, analyses in this paper are founded on a modern framework for handling extinction that eliminates the biases that accompany traditional approaches. As a consequence, zero points for distance indicators employed in the Hubble Space Telescope (HST) Key Project on the extragalactic distance scale (Freedman et al. 2001, hereafter HST-KP) must be updated using the same approach. Specifically, revised distances are required to the Ursa Major Cluster, which defines the Tully-Fisher (TF) relation employed here, and to the Coma Cluster, which defines the fundamental plane (FP) used to determine the distance of Maffei 1 in Paper I.

Behind the TF and FP calibrations are Cepheid distances to nearby galaxies, which in the HST-KP are anchored to the Large Magellanic Cloud (LMC). As a result, the period-luminosity (PL) relations for the LMC must be revisited. The HST-KP PL relations come from Udalski et al. (1999b), and the extinction corrections inherent to the PL relations, which are based on the apparent magnitude of the red clump, are those of Udalski et al. (1999a). Udalski et al. (1999a) presumed that the red clump has a constant absolute magnitude in Cousins $I$ (henceforth $I_C$) and that changes in apparent magnitude are due to fluctuations in extinction with respect to some zero point. The zero point was determined from color-magnitude diagrams for an eclipsing binary (HV 2274) and for two young open clusters. It appears that a reddening law for the LMC (Fitzpatrick 1985) was used to define $E(B - V)$ for each of these sources (see Udalski et al. 1998), but the determination of corrections to $E(B - V)$ from red clump magnitude fluctuations and the conversion of total reddenings to extinctions in $V$ and $I_C$ were based on extinction coefficients tabulated by Schlegel et al. (1998), which are based on the broadband reddening law of Cardelli et al. (1989) for the Milky Way.

Fortunately, the mean reddening of the Cepheids behind the HST-KP PL relations, $E(B - V) = 0.147$ mag (range 0.11–0.20 mag), is very close to the value measured for the objects defining the zero point (0.13–0.15 mag). This means that red clump adjustments to the Cepheid extinctions amount to second-order corrections, and any errors in these adjustments ought to average out. Thus, red clump stars are of less concern than the matter of what sets the zero point. The reddening that Udalski et al. (1999a) adopted for the binary was $0.149 \pm 0.015$ mag (Udalski et al. 1998). However, Guinan et al. (1998) derived $E(B - V) = 0.120 \pm 0.009$ mag by simultaneously solving for atmospheric temperatures and the interstellar extinction curve. In making their determination, Guinan et al. (1998) incorporated photometry from Udalski et al. (1998). This removed the reddening degeneracy that afflicted a preliminary determination criticized by Udalski et al. (1998). The result of Guinan et al. (1998) has to be taken very seriously because the SED, reddening law, and color excess are not only consistent with the LMC environment, but also consistent with each other. It is concluded that the $E(B - V)$ scale of Udalski et al. (1999a) is too high by 0.029 mag.

Correcting for the change in the reddening zero point, one gets $E(B - V) = 0.118$ mag for the mean reddening of LMC Cepheid fields as tracked by early-type stars. This is close to the value (0.10 mag) adopted by Madore & Freedman (1991).

According to Schlegel et al. (1998), $E(B - V) = 0.075$ mag is the Galactic reddening based on what is observed in anulli around the LMC. With the rest-frame elliptical SED of Pickles (2004) and the reddening law of Fitzpatrick (1999) tuned to give $A_{V}/E(B - V) = 3.07$ for Vega, the optical depth of Galactic dust toward the LMC at 1 $\mu$m is $\tau_{\text{gal}}^{\text{tot}} = 0.085$. Adopting the SED B12 III of Pickles (1998) for the stars in HV 2274, a heliocentric velocity of 265 km s$^{-1}$ (Freedman et al. 1983), and the reddening law of Gordon (2003) for dust inside the LMC, the mean value $E(B - V) = 0.118$ mag for the Cepheid fields leads to an optical depth $\tau_{\text{loc}}^{\text{tot}} = 0.040$ for dust “localized” in the LMC. In turn, applying the redshift and optical depths to SEDs of Cepheids, which here are adopted to be G0 supergiants based on the periods (there is hardly any difference in results...
between F8 I and G2 I), one gets the following sums of Galactic extinction, localized extinction, and the difference in $K$-corrections in $V$ and $I_C$: $A_V = 0.361$ mag (vs. 0.476 mag from Udalski et al. 1999a), $A_{I_C} = 0.202$ mag (vs. 0.288 mag from Udalski et al. 1999a), and $E(V-I_C) = 0.159$ mag (vs. 0.147 mag from Udalski et al. 1999a). This means that the zero points for the PL relations for the LMC Cepheids change as follows. For a distance modulus of 18.50 mag,

$$M_V = -2.760 \log (P - 1) - 4.103, \quad \text{(9)}$$
$$M_{I_C} = -2.962 \log (P - 1) - 4.818, \quad \text{(10)}$$
$$V - I_C = 0.202 \log (P - 1) + 0.715, \quad \text{(11)}$$

where $P$ is the period in days.

As the starting point for correcting HST-KP Cepheid distances, apparent distance moduli $\mu_V$ in $V$ and $\mu_{I_C}$ in $I_C$ recorded in the HST-KP were adopted. First, all were corrected to account for the new PL relations for the LMC (i.e., the revised extinction zero point for LMC Cepheids). Next, foreground values of $E(B - V)$ from Schlegel et al. (1998) were converted to $\tau_{I_C}$ by applying the reddening law of Fitzpatrick (1999) (tuned to give $K_V = 3.07$ for Vega) to the rest-frame elliptical SED of McCall (2004). Values of $\tau_{I_C}$ were derived individually for each galaxy from $\mu_V - \mu_{I_C}$, the redshift, and the SED of a G0 supergiant (a Cepheid), again using the reddening law of Fitzpatrick (1999). Then, values of Galactic extinction, $A^0_{I_C}$, localized extinction, $A^0_{I_C}$, and the $K$-correction, $K_{I_C}$, were computed. The corrections were subtracted from $\mu_{I_C}$ to arrive at corrected distance moduli $\mu^0_{I_C}$ on a scale where the distance modulus of the LMC is 18.50 mag. Note that $K_{I_C}$ can reach as high as 0.009 mag for a Virgo Cluster galaxy, so $K$-corrections are just starting to become relevant [$K_{I_C}$, of course, affects the determination of $\tau_{I_C}$ via $E(V-I_C)$]. Despite all of the revisions, Cepheid distances increased by only 0.007 ± 0.005 mag on average.

As in the HST-KP metallicity-corrected distance moduli $\mu^0_{I_C}$ were computed from oxygen abundances $\log Z = 12 + \log \left[n(O)/n(H)\right]$ estimated from H II regions via the calibration of $R_{33} = (\log [\text{O} II] \lambda3727 + [\text{O} III] \lambda4959 + [\text{O} III] \lambda5007)/[\text{H} \beta]$ provided by Zaritsky et al. (1994). Formally,

$$\mu^0_{I_C} = \mu^0_{I_C} + \delta_{I_C}, \quad \text{(12)}$$

where

$$\delta_{I_C} = \gamma_{I_C}(\log Z_{\text{LMC}} - \log Z). \quad \text{(13)}$$

From Sakai et al. (2004) $\gamma_{I_C} = -0.24$ and $\log Z_{\text{LMC}} = 8.50$. The adopted value of $\gamma_{I_C}$ is slightly more negative than that employed in the HST-KP.

Sakai et al. (2000) specify the Cepheid calibrators used to establish the zero point for the TF relation and in turn distances to the Ursa Major Cluster and Coma Cluster. Besides correcting the Cepheid distances, magnitudes for both the calibrators and the cluster galaxies must be recomputed using a self-consistent approach to extinction. To make this possible, S. Sakai (2005, private communication) provided the apparent magnitudes and corrections employed in the HST-KP. In the process, an error in the HST-KP Galactic extinction corrections was found; the $I_C$ band correction for all TF galaxies was accidentally set to 59% of the desired value.

For each Cepheid calibrator, new estimates of the Galactic extinction and the $K$-correction were computed from the value of $E(B - V)$ given by Schlegel et al. (1998) and the redshift using the SED of McCall (2004) closest to the revised Hubble type of the calibrator, adjusted appropriately for tilt. The internal extinction corrections of Sakai et al. (2000) were retained. With weights set by the random uncertainties in the absolute magnitudes, the mean offset between the new and old absolute magnitudes amounts to

$$M_{I_C} - M_{I_C} (\text{Sakai et al. 2000}) = +0.048 \text{ mag}. \quad \text{(14)}$$

Improved Galactic extinction and $K$-corrections for Ursa Major galaxies were computed from the mean value of $E(B - V)$ (from Schlegel et al. 1998) and redshift, which were judged from the mean cluster coordinates and velocity recorded by Sakai et al. (2000). To this end, the Sbc SED of McCall (2004) was adopted, adjusted to the mean tilt and luminosity of the local calibrators. For consistency with the calibrators, the corrections for internal extinction adopted by Sakai et al. (2000) were retained. With $E(B - V) = 0.025$ mag and a heliocentric velocity of 899 km s$^{-1}$, the weighted mean offset between the new and old apparent magnitudes corrected for Galactic extinction, redshift, and internal extinction amounts to

$$m^0_{I_C} (\text{UMa}) - m^0_{I_C} (\text{Sakai et al. 2000}) = -0.017 \text{ mag}. \quad \text{(15)}$$

The revisions to apparent and absolute magnitudes lead to an offset in the distance modulus for Ursa Major of

$$\mu^0_{I_C} (\text{UMa}) - \mu^0 (\text{Sakai et al. 2000}) = -0.065 \text{ mag}. \quad \text{(16)}$$

The distance modulus for Ursa Major determined by Sakai et al. (2000) was 31.58 mag, so the revised distance modulus comes out to be 31.515 ± 0.13 mag for an LMC distance modulus of 18.50 mag. The quoted error is the random error in the zero point of the TF relation.

The distance to the Coma Cluster adopted in this paper is the mean of results from the TF relation and the FP. The revision to the TF distance for Coma was undertaken in exactly the same manner as that for Ursa Major. Apparent magnitudes shift as follows:

$$m^0_{I_C} (\text{Coma}) - m^0_{I_C} (\text{Sakai et al. 2000}) = -0.015 \text{ mag}. \quad \text{(17)}$$

Combining this with the absolute magnitude shift computed above for the Cepheid calibrators, the distance modulus shifts by

$$\mu^0_{I_C} (\text{Coma}) - \mu^0 (\text{Sakai et al. 2000}) = -0.063 \text{ mag}. \quad \text{(18)}$$

Since Sakai et al. (2000) derived a distance modulus of 34.74 mag, the new distance modulus for Coma works out to be 34.677 ± 0.13 mag, where the uncertainty is the random error in the zero point of the TF relation.

The FP analysis for the HST-KP was conducted by Kelson et al. (2000). For any particular galaxy, the zero point of the FP is defined by

$$\gamma = \log r_c - 1.24 \log \sigma + 0.82 \log (l) e,$$
where $r_e$ is the effective metric radius (of an $r^{1/4}$ law), $\sigma$ is the velocity dispersion, and $\langle I \rangle_e$ is the mean surface brightness within the effective radius. Of course, one does not measure $r_e$, but rather $\theta_e$, the effective radius in angular units. If $r_e$ is replaced by $\theta_e$, variations in $\gamma$ from galaxy to galaxy arise from variations in distance. The fiducial value of $\gamma$ was defined using the Leo Group, the Virgo Cluster, and the Fornax Cluster, in which Cepheid calibrators are located. Revisions to extinction or to $K$-corrections affect $\gamma$ through $\langle I \rangle_e$ and through $r_e$, the latter being determined by the distances assigned to the reference clusters (which depend on the treatment of Cepheids).

Photometry in $V$ was used to define $\gamma$ for Leo, Virgo, and Fornax, and photometry in Gunn $r$ was used to define $\gamma$ for the Coma Cluster. Revising extinction estimates as recommended by McCall (2004) and computing $K$-corrections self-consistently, the changes to $\langle I \rangle_e$ decrease the weighted mean value of $\gamma$ for the calibrating clusters by 0.0013 and decrease the value of $\gamma$ for Coma by 0.0065. The revised Cepheid analysis described above moves the distance moduli for Leo, Virgo, and Fornax farther away by 0.012 mag on average with respect to the distance moduli adopted in the $HST$-KP. In this computation, clusters were weighted on the basis of the uncertainty in $\gamma$ (Kelson et al. 2000). The combination of all effects leads to an increase in the distance modulus of the Coma Cluster by 0.038 mag with respect to the $HST$-KP. On a scale where the distance modulus of the LMC is 18.50 mag, the revised distance modulus to Coma becomes 34.705 ± 0.15 mag, where the uncertainty is that due to random errors.

The distance moduli for Coma derived from the TF relation and the FP differ by only 0.028 mag. We adopt the unweighted average, which is 34.69 ± 0.10 mag.

In this paper the authors prefer to adopt the maser distance to NGC 4258 as the zero point for distances, rather than the LMC. This galaxy was among the Cepheid calibrators in the $HST$-KP. From the reanalysis above, $\mu_0^B$(N4258) = 29.526 mag with a random error of 0.07 mag. This is 0.016 mag higher than the $HST$-KP value. From Herrnstein et al. (1999; see also Gibson 2000), $\mu$(masers) = 29.29 mag, so

$$\mu(\text{masers}) - \mu(\text{Cepheids}) = -0.236 \text{ mag.} \quad (20)$$

Referring to the maser zero point, the distance moduli for Ursa Major and Coma are 31.28 ± 0.08 mag and 34.45 ± 0.10 mag, respectively.

A proper treatment of the shift in the $HST$-KP Hubble constant ($H_0$) due to the above extinction corrections would necessitate a reanalysis of the zero points for all distance indicators behind the measurement. Since our distance measurements to Maffei 2 and IC 342 do not depend on $H_0$, we do not require a value of $H_0$ on the extinction and distance scale adopted in this paper. However, for the sake of the discussion in §7 in which we compare the new distance to the IC 342/Maffei Group with that implied by the Hubble flow, we adopt the $HST$-KP value of $H_0 = 72 \text{ km s}^{-1}\text{ Mpc}^{-1}$ after (1) correcting for the mean increase of $0.007 ± 0.005 \text{ mag}$ in the distance moduli of the Cepheid calibrators due to the extinction corrections described above, and (2) correcting for the decrease of 0.236 mag in all $HST$-KP distance moduli due to the shift from the LMC to the maser zero point. After applying these corrections, we obtain $H_0 = 80.0 \text{ km s}^{-1}\text{ Mpc}^{-1}$. This value is consistent with the most recent measurement of $77 ± 11 \text{ km s}^{-1}\text{ Mpc}^{-1}$ obtained from the Sunyaev-Zel’dovich effect measured by the Chandra X-Ray Observatory for high-redshift galaxy clusters (Bonamente et al. 2006), a result that is completely independent of the $HST$-KP. In addition, Ciardullo et al. (2002) use the planetary nebula luminosity function (PNLF) to derive a distance to NGC 4258 that is in close agreement with the maser distance and that increases the $HST$-KP value of $H_0$ to 78 ± 7 km s$^{-1}$ Mpc$^{-1}$. The agreement between these two studies substantiates the distance scale adopted in this paper.

6.2. The Distance to Maffei 2

For a very long time, studies of Maffei 2 were encumbered by the lack of an apparent magnitude. A reliable measurement of the total apparent magnitude of Maffei 2 was finally made by Buta & McCall (1999) in $I$, which allows application of the TF relation to determine the distance. We require a TF relation in which the luminosity diagnostic is derived from H I rotation curves as opposed to line widths, owing to the contamination of Galactic H I in the H I line profile of Maffei 2. As a TF relation of this form was not available in $I$, we constructed the relation from the $I$-band photometry and H I synthesis observations of spiral galaxies in the Ursa Major (UMa) Cluster conducted by Verheijen (2001, hereafter V01). For the distance modulus of UMa, we adopted 31.28 ± 0.08 mag (see § 6.1). Of the rotational velocity parameters measured by V01, we chose the plateau rotational velocity ($V_{\text{flat}}$), defined as the average amplitude of the flat outer region of the rotation curve. V01 found the least scatter in the TF relation constructed from this diagnostic, as opposed to the maximum observed rotational velocity. We restricted our TF analysis to spiral galaxies for which $V_{\text{flat}}$ could be measured with confidence (referred to by V01 as the RC/DF sample). For consistency with the galaxy sample from which our adopted UMa distance was derived, we excluded the six galaxies from the RC/DF sample with $I$-band tilt corrections greater than 0.6 mag. We also excluded NGC 3992 based on the arguments of V01 that the galaxy may be in the background of UMa. Our final sample of TF calibrators contains 15 spiral galaxies.

Great care was taken to correct the TF ingredients in the same manner as for Maffei 2. Galactic extinctions were computed from SFD98 reddenings as described in § 5.1. The total $A_I$ magnitude of each galaxy was corrected to its face-on value by employing YES to solve for the internal extinction from the rotational velocity and the apparent axis ratio (see McCall 2004). $K$-corrections to the UMa photometry were found to be negligible in $I$ (less than 0.01 mag). The TF data are given in Table 5 and plotted in Figure 3.

To construct the TF relation, we followed the treatment of $HST$-KP and determined the slope and zero point using a bivariate linear fit, minimizing errors in both log 2 $V_{\text{flat}}$ and $M_I$. As in V01, we assumed that all galaxies have equal relative uncertainties of 5% in $V_{\text{flat}}$ and equal photometric uncertainties of 0.05 mag in $M_I$. The fit yields

$$M_I = (-10.52 ± 0.49) \log 2V_{\text{flat}} + (4.77 ± 1.22), \quad (21)$$

with an rms scatter of 0.33 mag in $M_I$. The scatter is due in large part to the depth of the UMa Cluster; the virial radius of 880 kpc (Tully et al. 1996) corresponds to a range of 0.21 mag in $M_I$, which is comparable to the rms deviation over and above the measurement uncertainties.

Our fit is in close agreement with V01, who found a slope, zero point, and rms scatter of $-10.4 ± 0.4$, $4.27 ± 0.89$ mag, and 0.30 mag, respectively, using the same galaxy sample but anchored to a UMa distance of 18.6 Mpc and employing different correction methods for the Galactic and internal extinction. We also note that equation (21) is consistent with the relation
TABLE 5
TULLY-FISHER PARAMETERS

| Galaxy  | Type (1) | i (deg) | q (4) | V_0 (km s^{-1}) | V_{flat} (km s^{-1}) | I (mag) | m (mag) | A_I (mag) | A_e (mag) | M_l (mag) |
|---------|----------|---------|-------|----------------|---------------------|--------|--------|-----------|-----------|-----------|
| NGC 3726 | Sc       | 53      | 0.62  | 865.6         | 162 ± 9             | 9.51   | 0.019  | 0.03      | 0.18      | -21.98    |
| NGC 3729 | Sab      | 49      | 0.68  | 1059.8        | 151 ± 11            | 10.30  | 0.012  | 0.02      | 0.13      | -21.13    |
| NGC 3917 | Scd      | 79      | 0.24  | 964.6         | 135 ± 3             | 10.85  | 0.025  | 0.04      | 0.60      | -21.06    |
| NGC 3949 | Sbc      | 55      | 0.62  | 800.2         | 164 ± 7             | 10.28  | 0.024  | 0.04      | 0.18      | -21.22    |
| NGC 3953 | Sbc      | 62      | 0.5   | 1052.3        | 223 ± 5             | 9.02   | 0.034  | 0.05      | 0.36      | -22.67    |
| NGC 4085 | Sc       | 82      | 0.24  | 745.7         | 134 ± 6             | 11.28  | 0.020  | 0.03      | 0.59      | -20.62    |
| NGC 4088 | Sbc      | 69      | 0.37  | 756.7         | 173 ± 14            | 9.37   | 0.023  | 0.04      | 0.46      | -22.41    |
| NGC 4100 | Sbc      | 73      | 0.29  | 1074.4        | 164 ± 13            | 10.00  | 0.026  | 0.04      | 0.58      | -21.90    |
| NGC 4102 | Sab      | 56      | 0.56  | 846.3         | 178 ± 11            | 9.93   | 0.023  | 0.04      | 0.25      | -21.63    |
| NGC 4138 | Sa       | 53      | 0.63  | 893.8         | 147 ± 12            | 10.09  | 0.016  | 0.03      | 0.16      | -21.37    |
| UGC 6399 | Sm       | 75      | 0.28  | 791.5         | 88 ± 5              | 12.88  | 0.018  | 0.03      | 0.00      | -18.43    |
| UGC 6446 | Sd       | 51      | 0.62  | 644.3         | 82 ± 4              | 12.58  | 0.018  | 0.03      | 0.05      | -18.78    |
| UGC 6667 | Scd      | 89      | 0.12  | 973.2         | 86 ± 3              | 12.63  | 0.019  | 0.03      | 0.56      | -19.24    |
| UGC 6917 | Sd       | 56      | 0.54  | 910.7         | 104 ± 4             | 11.74  | 0.031  | 0.05      | 0.14      | -19.73    |
| UGC 6983 | Scd      | 49      | 0.66  | 1081.9        | 107 ± 7             | 11.91  | 0.031  | 0.05      | 0.09      | -19.51    |

Maffei 2: Scb^a 67b 0.421^a -23b 170 ± 4^b 9.29^c 2.01^d 3.15^d 0.37 -21.87^d

Notes.—Col. (1): Name of the galaxy. Col. (2): Morphological type from Verheijen (2001). Col. (3): Adopted inclination angle from Verheijen (2001). Col. (4): Ratio of the semiminor to the semimajor axis from Verheijen & Sancisi (2001). Col. (5): Heliocentric radial velocity from Verheijen (2001). Col. (6): Mean rotational velocity of the flat part of the galaxy’s rotation curve, corrected for inclination. Col. (7): Apparent total magnitude in I from Verheijen (2001). Col. (8): Optical depth of dust at 1 μm calculated from the Schlegel et al. (1998) value of E(B − V) (see § 5.1). Col. (9): Galactic extinction correction I computed from γI using YES. Col. (10): Internal extinction correction in I from YES (see § 6.2). Col. (11): Absolute I magnitude, corrected for Galactic extinction and inclination. K-corrections at the redshift of the UMa Cluster are negligible in the near-infrared. The adopted distance modulus to the cluster is 31.28 (see § 6.1).

— a Buta & McCall (1999).
— b Hurt et al. (1996).
— c Uncertainties are given in Table 6.
— d This study.

found by Sakai et al. (2000) for a sample containing both field and cluster galaxies, which demonstrates that the relation does not vary significantly with environment.

The TF parameters for Maffei 2 are given in Table 5. Using our I-band TF relation (eq. [21]), we obtain a distance to Maffei 2 of 3.34 ± 0.56 Mpc (μ = 27.62 ± 0.36 mag). The random uncertainty is computed from

\[
\langle \delta M_f \rangle^2 = (m \delta \log 2V_{\text{flat}})^2 + \langle \delta m \rangle^2 (\log 2V_{\text{flat}} - \langle \log 2V_{\text{flat}} \rangle)^2
\]

where \( \delta m \) is the standard error associated with the slope \( m \) of the TF relation (eq. [21]), \( \delta \log 2V_{\text{flat}} \) is the uncertainty in the estimate of \( \log 2V_{\text{flat}} \) for Maffei 2, \( \sigma_M \) is the rms deviation in \( M_f \) of the 15 galaxies in the V01 sample, and \( \langle \log 2V_{\text{flat}} \rangle \) is the mean value of \( \log 2V_{\text{flat}} \) for the V01 sample, found to be 2.45. The systematic uncertainty associated with the calibration of the distance to the UMa Cluster amounts to 0.13 mag.

V01 also measured total K’ magnitudes and report a K’-band TF relation with a slightly reduced scatter of 0.26 mag in \( M_{K'} \) as opposed to 0.33 mag in \( M_f \). Maffei 2 has been observed in \( K_s \) by the Two Micron All Sky Survey (2MASS), and an estimate of its total magnitude, \( K_{\text{m_ext}} \), is available. However, we find that the values of \( K_{\text{m_ext}} \) reported by 2MASS for the V01 sample differ considerably from the total \( K' \) magnitudes measured by V01, with a mean difference of 0.3 ± 0.4 mag and the discrepancy reaching as high as 1.2 mag. The large standard deviation in the residuals reflects a significant difference in the measurement techniques adopted by the two surveys. The V01 total magnitude of a galaxy was obtained by integration of the fit to the growth curve out to infinity, while the 2MASS extrapolated magnitude was computed by integration of the fit out to a finite radius judged to contain the extent of the galaxy. Hence, the V01 total magnitudes allow for a more meaningful comparison of the integrated properties. Further evidence of this is the significantly larger scatter of 0.52 mag found for the TF relation constructed from the 2MASS \( K_{\text{m_ext}} \) magnitudes for the V01 sample.

In an attempt to derive a transformation from 2MASS to V01 magnitudes, we investigated the magnitude residuals as a function of various galaxy parameters. The only dependency we observed is on the apparent \( K' \)-band central disk surface brightness, \( \mu_0(K') \), from Tully et al. (1996) in the sense that \( K_{\text{m_ext}} - K' \) is larger for the galaxies with low surface brightness [i.e., \( \mu_0(K') > 17 \) mag arcsec\(^{-2} \)]. This is illustrated in Figure 4. Unfortunately,
the large scatter in $k_{\text{m, ext}} - K'$ does not allow for a reliable estimate of a $K'$ magnitude for Maffei 2 from $k_{\text{m, ext}}$. The lack of a V01 measurement of the total $K'$ magnitude for Maffei 2 therefore precludes a reliable TF distance in this bandpass, so we adopt the $I$-band value of 3.34 Mpc.

6.3. The Distance to IC 342

The small inclination of IC 342 makes it difficult to determine an accurate distance from the TF relation. However, recent observations of Cepheids make possible a reliable determination from the PL relation. Saha et al. (2002) observed Cepheid variables in IC 342 in Thuan-Gunn $r$ and $i$, deriving a distance modulus of 27.58 ± 0.18 mag and extinction $A_V = 2.01 ± 0.32$ mag. However, the adopted PL relations for $r$ and $i$ were taken from Hoessel et al. (1994), who derived them from the LMC relations for Cousins $R$ and $I$ presented by Madore & Freedman (1991), who in fact employed a different I-band PL relation from that adopted in the HST-KP. Also, the transformation equations employed to get the PL relations in $r$ and $i$ (Wade et al. 1979) were founded on Johnson $R$ and $I$ (hereafter $R_1$ and $I_1$), not Cousins $R$ and $I$ (hereafter $R_2$ and $I_2$). Thus, a reexamination of the Cepheid distance is in order.

PL relations for the LMC in $R_1$ and $I_1$ have been derived by combining the HST-KP relations for $V$ and $I_1$ as revised in § 6.1, the period-color relation for $V - R_C$ (Madore & Freedman 1991), and transformation equations connecting $V - R_C$ to $V - R_1$ and $V - I_1$ to $V - I_1$ (Bessell 1979). In turn, revised PL relations for $r$ and $i$ have been derived from those for $R_1$ and $I_1$ using the transformation equations of Wade et al. (1979). On a scale where the LMC is at a distance modulus of 18.50 mag,

$$M_r = -3.002(\log P - 1) - 4.104, \quad (23)$$

$$M_i = -3.012(\log P - 1) - 4.159, \quad (24)$$

where $P$ is the period in days. With the new PL relations, the mean apparent distance moduli in $r$ and $i$ for the Cepheids in IC 342 become $\mu_r = 29.100 ± 0.045$ mag and $\mu_i = 28.712 ± 0.042$ mag, respectively, and the mean color excess becomes $E(r-i) = \mu_r - \mu_i = 0.388 ± 0.036$ mag. The color excess permits a solution for the optical depth of dust localized in IC 342 ($\tau_{100}^{\text{loc}}$), since the optical depth of Galactic dust at 1 $\mu$m has been shown to be $\tau_{100}^{\text{gal}} = 0.677 ± 0.056$ (§ 5.3). Knowledge of the optical depth of both components then permits corrections for extinction in $r$ and $i$. Calculations have been accomplished with YES using the reddening law of Fitzpatrick (1999) tuned to give $A_V/E(B-V) = 3.07$ for Vega (see McCaill 2004).

Adopting a heliocentric velocity of 25 km s$^{-1}$ (Buta & McCaill 1999), the observed mean color excess of the Cepheids gives $\tau_{100}^{\text{loc}} = 0.056 - 0.064$ for spectral types between F8 I and G2 I, typical of luminous Cepheids. Solving for the Galactic and localized components of the extinction in $i$ over the same span of spectral types (the $K$-correction is negligible), the true distance modulus $\mu_0$ ranges from 27.504 to 27.492 mag.

The distance modulus can be corrected for metallicity using observations of H II regions in IC 342 made by McCall et al. (1985). As was done for HST-KP Cepheids, measurements of $R_{23}$ across the disk were converted to oxygen abundances using the calibration of Zaritsky et al. (1994). Based on their positions, the appropriate mean metallicity to adopt for the Cepheids observed in IC 342 is $<\log Z> = 9.12$. With $<\log Z_{\text{LMC}}> = 8.50$ (Sakai et al. 2000), the corrected distance modulus is $\mu_0 = 27.643 ± 0.120$ mag on the scale where the LMC is at 18.50 mag. The uncertainty is that due to random errors, specifically the quadrature sum of the errors associated with $E(r-i)$ and with the apparent distance modulus in $i$. The result is 0.06 mag higher than the value estimated by Saha et al. (2002). Note also that the revised extinction of the Cepheids in $V$ is 2.10 mag (Galactic plus localized), which is 0.09 mag more than estimated by Saha et al. (2002). Correcting to the maser zero point, the distance modulus for IC 342 becomes 27.41 ± 0.12 mag.

6.4. The Distance to Maffei 1

Recently, the extinction of Maffei 1 was found from the color-Mg$_2$ relation to be $\tau_{100}^{\text{gal}} = 1.691 ± 0.066$ (Paper I). The corresponding broadband extinctions were derived from extinction coefficients computed by an older version of YES than that employed in this paper for Maffei 2 and IC 342. In the updated version of YES, the accuracy of extinction computations has increased owing to improvements in the template SEDs (see McCaill 2004). For consistency with the treatment of Maffei 2 and IC 342, we have recomputed the extinction parameters of Maffei 1 using the same version of YES employed in this paper. The revised extinction coefficients, broadband extinctions, and extinction-corrected magnitudes for Maffei 1 are given in Table 6. Paper I used the I-band FP relation constructed from elliptical galaxies in the Coma Cluster to determine the distance to Maffei 1. The authors arrived at a distance of 2.99 ± 0.30 Mpc, which is the weighted mean of their FP estimate combined with measurements from the $D_n$ relation of Lynden-Bell et al. (1988) using photometry in $B$ and $K'$. The $D_n \sigma$ distance estimates depend on the Hubble constant. To place $H_0$ on the same extinction scale as that adopted in this paper, one would require a reanalysis of all HST-KP zero points (see § 6.1). Given that the two $D_n \sigma$ distances to Maffei 1 are consistent within errors with the FP distance derived for this galaxy, here we adopt the FP distance alone in order to obtain a value that is on the same extinction and distance scale as the distances to Maffei 2 and IC 342 derived in this paper. The FP estimate depends on the I-band extinction of Maffei 1, as well as the adopted distance to the Coma Cluster. The modifications to the extinction of Maffei 1 and the distance to the Coma Cluster (see § 6.1) result in a revised distance to Maffei 1 of 2.85 ± 0.36 Mpc (corrected to the NGC 4258 maser zero point).

7. IMPLICATIONS FOR THE IC 342/MAFFEI GROUP

The I-band imaging of Buta & McCaill (1999) revealed a close grouping of galaxies apparently dominated by the spiral galaxies
Maffei 2 and IC 342 and the giant elliptical Maffei 1. Unfortunately, the gross uncertainties in the distances to these three galaxies, owing to their heavy obscuration, precluded a definitive statement about their relative positions and luminosities. The results of this paper now allow for a reliable comparison of all three galaxies.

The revised properties of Maffei 1, Maffei 2, and IC 342 are summarized in Table 6. All values are now anchored to the same distance and extinction scale. The implications of our results for these three galaxies are as follows:

1. The distances found in this study place the three galaxies within 0.49 Mpc in depth. Their maximum spread in angle is 10°, which corresponds to a metric distance of 0.53 Mpc at the average distance to the galaxies of 3.03 ± 0.15 Mpc.

2. Maffei 1, Maffei 2, and IC 342 have nearly identical face-on luminosities, spanning a range of only 0.02 mag in $M_V$. As predicted by Spinrad et al. (1973), Maffei 2 suffers more Galactic extinction than Maffei 1 by nearly a full magnitude in $V$. Although a magnitude fainter in $M_V$ than M31, the three galaxies clearly dominate the IC 342/Maffei Group. The next brightest member, Dwingeloo 1, has a rotational velocity comparable to M33 and can be considered to be ~2 mag fainter than the giants in $I$.

3. Velocities in the Local Group reference frame, computed using the solar apex vector of Courteau & van der Bergh (1999), are 311, 22, and 255 km s$^{-1}$ for Maffei 1, Maffei 2, and IC 342, respectively. These values significantly exceed the velocity dispersion of 61 km s$^{-1}$ for the Local Group (Courteau & van der Bergh 1999), placing all three galaxies well beyond its dynamical range.

Previously, the role that Maffei 1, Maffei 2, and IC 342 have played in the evolution of the Milky Way and its neighbors has been a subject of controversy due to their uncertain distances. Early estimates of the radial velocities and distances to Maffei 1 and IC 342 suggested that the galaxies could have been in the vicinity of the Local Group within the last 7 billion years, thereby affecting the early dynamical evolution of the Local Group (Valtonen et al. 1993). Shortly following this analysis, Krismer et al. (1995) used the angular separations and radial velocities of 12 galaxies identified as members of the IC 342/Maffei Group to argue that the evolution of the group must have been independent of the Local Group. More recently, distances to several dwarf galaxies in the IC 342/Maffei Group have been derived by Karachentsev et al. (2003) via the tip of the red giant branch (TRGB), placing the dwarfs outside the early dynamical influence of the Local Group. However, past distance estimates to Maffei 2 were too uncertain to ascertain its placement within the group or its role as a dominant member. The modern, homogeneous properties presented in this paper for all three galaxies firmly establish the existence of a compact group of galaxies dominated by three giants at an average distance of 3.03 Mpc from the Milky Way. The mean velocity of the galaxies relative to the Local Group is 253 km s$^{-1}$. Assuming a smooth Hubble flow with $H_0 = 80.0$ km s$^{-1}$ Mpc$^{-1}$ (see §6.1), the Hubble distance to the IC 342/Maffei Group is 3.17 Mpc. This is in close agreement with the mean distance of 3.03 ± 0.15 Mpc found in this study. It is therefore highly unlikely that the dominant members of the IC 342/Maffei Group have interacted with the Local Group since the big bang. This conclusion lends credence to the timing model of Kahn & Woltjer (1959), which is based on the simple evolutionary scenario of a two-body system involving M31 and the Milky Way with negligible perturbation from other galaxies. The model provides an estimate for the age of the universe and mass of the Local Group, in particular offering strong evidence that most of the mass in the Local Group is dark. The predictions of the model are therefore strengthened by the results of this study.

8. SUMMARY

We have constructed a correlation between dust and gas in spiral galaxies as a tool for determining the Galactic extinction

| Property | Symbol | Units | Maffei 1 | Maffei 2 | IC 342 |
|----------|--------|-------|---------|---------|--------|
| Apparent magnitudes$^a$ | $B_T$ | mag | 13.47 ± 0.09 | 14.77 ± 0.29 | 9.37 ± 0.03 |
| | $V_T$ | mag | 11.14 ± 0.06 | 12.41 ± 0.08 | 8.31 ± 0.03 |
| | $I_T$ | mag | 8.06 ± 0.04 | 9.29 ± 0.06 | 6.68 ± 0.03 |
| Galactic optical depth at 1 μm | $\tau_1$ | ... | 1.691 ± 0.066 | 2.017 ± 0.211 | 0.677 ± 0.056 |
| Extinction normalized to $\tau_1$ computed by YES | $R_B$ | ... | 3.623 | 3.654 | 3.749 |
| | $R_V$ | ... | 2.765 | 2.767 | 2.831 |
| | $R_I$ | ... | 1.571 | 1.564 | 1.588 |
| Galactic extinction | $A_B$ | mag | 6.128 ± 0.241 | 7.371 ± 0.770 | 2.537 ± 0.208 |
| | $A_V$ | mag | 4.677 ± 0.184 | 5.581 ± 0.583 | 1.916 ± 0.157 |
| | $A_I$ | mag | 2.658 ± 0.104 | 3.155 ± 0.329 | 1.075 ± 0.088 |
| Internal extinction (excess over face-on) | $A_B^I$ | mag | ... | 0.646 | 0.099 |
| | $A_V^I$ | mag | ... | 0.548 | 0.081 |
| | $A_I^I$ | mag | ... | 0.385 | 0.053 |
| Apparent face-on magnitudes corrected for Galactic extinction$^b$ | $B_0$ | mag | 7.34 ± 0.26 | 6.75 ± 0.82 | 6.73 ± 0.21 |
| | $V_0$ | mag | 6.46 ± 0.19 | 6.28 ± 0.59 | 6.31 ± 0.16 |
| | $I_0$ | mag | 5.40 ± 0.11 | 5.75 ± 0.33 | 5.55 ± 0.09 |
| Distance modulus | $\mu$ | mag | 27.28 ± 0.27 | 27.62 ± 0.36 | 27.41 ± 0.12 |
| Distance | $d$ | Mpc | 2.85 ± 0.36 | 3.34 ± 0.56 | 3.03 ± 0.17 |
| Absolute face-on magnitudes corrected for Galactic extinction | $M_B$ | mag | −19.93 ± 0.38 | −20.86 ± 0.90 | −20.68 ± 0.24 |
| | $M_V$ | mag | −20.81 ± 0.33 | −21.34 ± 0.69 | −21.10 ± 0.20 |
| | $M_I$ | mag | −21.87 ± 0.30 | −21.87 ± 0.49 | −21.86 ± 0.15 |

$^a$ Buta & McCall (1999).

$^b$ Cosmological corrections at this redshift are negligible.
of a heavily obscured spiral. The correlation can be used to estimate the extragalactic extinction of constituent H ii regions from measurements of the column density of hydrogen in the heavily obscured galaxy. The spiral’s Galactic extinction can then be determined by taking the average difference between the extragalactic extinction and the total extinction of each H ii region found from observations of the Balmer decrement.

We have used the dust-gas correlation to measure the Galactic extinction of the heavily obscured spiral galaxies Maffei 2 and IC 342, for which we find values of $\tau_{\text{gal}} = 0.217 \pm 0.011$ and $\tau_{\text{gal}} = 0.692 \pm 0.066$, respectively, where $\tau_{\text{gal}}$ is the optical depth of Galactic dust at 1 $\mu$m. The Galactic extinction of Maffei 2 is the most accurate measurement to date, while the result for IC 342 is consistent with the optical depth of 0.639 $\pm$ 0.102 obtained from the reddening maps of Schlegel et al. (1998). We therefore adopt the weighted mean of the two values for IC 342, which yields $\tau_{\text{gal}} = 0.677 \pm 0.056$. Thus, $A_I = 5.58 \pm 0.58$ mag for Maffei 2 and $A_I = 1.92 \pm 0.16$ mag for IC 342. The reddening coefficients used in this analysis were computed by the York Extinction Solver (YES), which accounts for the color-dependent shifts in the effective wavelengths of broadband filters.

To facilitate distance determinations, we have reanalyzed the zero points of the extragalactic distance scale using the approach to extinction adopted for the galaxies in the IC 342/Maffei Group.

To determine the distance to Maffei 2, we have formulated the Tully-Fisher (TF) relation in $I$ using rotation curves instead of H I line widths as the luminosity diagnostic, as line widths for nearby galaxies like Maffei 2 can be unreliable due to contamination by Galactic H I. The TF distance to Maffei 2 is found to be $3.34 \pm 0.56$ Mpc, where the zero point is set by the maser distance to NGC 4258. Using the extinction treatment and distance scale adopted in this paper, we rederive the Cepheid distance to IC 342 (Saha et al. 2002) and the FP distance to Maffei 1 (Paper I), obtaining $3.03 \pm 0.17$ Mpc and $2.85 \pm 0.36$ Mpc, respectively. The revised distances and magnitudes reveal that the IC 342/Maffei Group is dominated by three giant galaxies with nearly identical luminosities. Further, the average distance to the three galaxies is in excellent agreement with expectations for the Hubble Flow, making it highly unlikely that these galaxies interacted with the Local Group since the big bang.

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REFERENCES

Arimoto, N., Sofue, Y., & Tsujimoto, T. 1996, PASJ, 48, 275
Bessell, M. S. 1979, PASP, 91, 589
Blair, W., Kirshner, R., & Chevalier, R. A. 1982, ApJ, 254, 50
Bonamente, M., Joy, M. K., La Roque, S. J., Carlstrom, J. E., Reese, E. D., & Dawson, K. S. 2006, ApJ, 647, 25
Bosma, A., Goss, W. M., & Allen, R. 1981, A&A, 93, 106
Bottinelli, L., Chamales, P., Gerard, F., Gougenheim, L., Heidmann, J., Kazes, I., & Lauer, R. 1971, A&A, 12, 264
Buta, R. J., & McCall, M. L. 1999, ApJS, 124, 33
Cordelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245
Ciardullo, R., Feldmeier, J. J., Jacoby, G. H., Kuzio de Naray, R., Laychak, M. B., & Durrell, P. R. 2002, ApJ, 577, 31
Courteau, S., & van den Bergh, S. 1999, AJ, 118, 337
Crossthwaite, L. P., Turner, J. L., Hurt, R. L., Levine, D. A., Martin, R. N., & Courteau, S., van den Bergh, S. 1999, AJ, 118, 337
Freeman, K. C., Illingworth, G., & Oemler, A., Jr. 1983, ApJ, 272, 488
Freedman, W. L., et al. 2001, ApJ, 553, 47
———. 1999, PASP, 111, 631
———. 1992, PASP, 104, 362
Maffei, P. 1968, PASP, 80, 618
Malhotra, S. 1994, ApJ, 433, 687
———. 1995, ApJ, 448, 138
Mason, A. M., & Wilson, C. D. 2004, ApJ, 612, 860
McCall, M. L. 1982, Ph.D. thesis, Univ. Texas at Austin
McGee, G. R. 1984, MNRAS, 207, 801
———. 1989, AJ, 97, 1341
———. 2004, AJ, 128, 2144
McCall, M. L., Rybski, P. M., & Shields, G. A. 1985, ApJS, 57, 1
McGaugh, S. S. 1991, ApJ, 380, 140
Newton, K. 1980a, MNRAS, 191, 169
———. 1980b, MNRAS, 191, 169
Oke, J. B. 1990, AJ, 99, 1621
Pickles, A. J. 1998, PASP, 110, 863
Rayo, J. F., Peimbert, M., & Torres-Peimbert, S. 1982, ApJ, 255, 1
Saha, A., Claver, J., & Hoessel, J. G. 2002, AJ, 124, 839
Sakai, S., Ferrarese, L., Kennicutt, R. C., Jr., & Saha, A. 2004, ApJ, 608, 42
Sakai, S., et al. 2000, ApJ, 529, 698
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525 (SFD98)
Shields, G. A., & Skillman, E. D. 1991, ApJ, 371, 82
Skillman, E. D., Kennicutt, R. C., Jr., Shields, G. A., & Zaritsky, D. 1996, ApJ, 462, 147
Spinrad, H., Bahecall, J., Becklin, E. E., Gunn, J. E., Kristian, J., Neugebauer, G., Sargent, W. L. W., & Smith, H. 1973, ApJ, 180, 351
Storey, P. J., & Hummer, D. G. 1995, MNRAS, 272, 41
Tilanus, R. P. J., & Allen, R. J. 1991, A&A, 244, 8
Tully, R. B., Verheijen, M. A. W., Pierce, M. J., Huang, J., & Wainscoat, R. J. 1996, AJ, 112, 2471
Udalski, A., Pietrzyński, G., Woźniak, P., Szymański, M., Kubiaκ, M., & Zebiuk, K. 1998, ApJ, 509, L25
Udalski, A., Soszynski, I., Szymanski, M., Kubiak, M., Pietrzynski, G., Wozniak, P., & Zebrun, K. 1999a, Acta Astron., 49, 223
Udalski, A., Szymanski, M., Kubiak, M., Pietrzynski, G., Soszynski, I., Wozniak, P., & Zebrun, K. 1999b, Acta Astron., 49, 201
Valtonen, M. J., Byrd, G. G., McCall, M. L., & Innanen, K. A. 1993, AJ, 105, 886
van der Kruit, P. C. 1986, A&A, 157, 230
Verheijen, M. A. W. 2001, ApJ, 563, 694 (V01)
Verheijen, M. A. W., & Sancisi, R. 2001, A&A, 370, 765

Vilchez, J. M., Pagel, B. E., Diaz, A. I., Terlevich, E., & Edmunds, M. G. 1988, MNRAS, 235, 633
Wade, R. A., Hoessel, J. G., Elias, J. H., & Huchra, J. P. 1979, PASP, 91, 35
Warmels, R. H. 1988, A&AS, 72, 427
Wevers, B. M. H. R., van der Kruit, P. C., & Allen, R. J. 1986, A&AS, 66, 505
Wilson, C. D. 1995, ApJ, 448, L97
Young, J. S., et al. 1995, ApJS, 98, 219
Zaritsky, D., Kennicutt, R. C., Jr., & Huchra, J. P. 1994, ApJ, 420, 87