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THE EXTINCTION AND DISTANCE OF MAFFEI 1

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ABSTRACT

We have obtained low- and high-resolution spectra of the core of the highly reddened elliptical galaxy Maffei 1. From these data, we have obtained the first measurement of the Mg₂ index and have measured the velocity dispersion and radial velocity with improved accuracy. To evaluate the extinction, a correlation between the Mg₂ index and effective $V-I$ color has been established for elliptical galaxies. Using a new method for correcting for effective wavelength shifts, the $V-I$ color excess reveals that the optical depth of Galactic dust at 1 μm is 1.69 ± 0.07 . Thus, $A_V = 4.67 \pm 0.19$ mag, which is lower by 0.4 mag than previously thought. To establish the distance, the fundamental plane for elliptical galaxies has been constructed in I . The velocity dispersion of Maffei 1, measured to be 186.8 ± 7.4 km s⁻¹, in combination with modern wide-field photometry in I , leads to a distance of 2.92 ± 0.37 Mpc. The $D_n-\sigma$ relation, which is independently calibrated, gives 3.08 ± 0.85 and 3.23 ± 0.67 Mpc from photometry in B and K' , respectively. The weighted mean of the three estimates is 3.01 ± 0.30 Mpc, which is lower than distances judged with reference to M32 and the bulge of M31 from the brightest stars seen at K' . Since the luminosity of asymptotic giant branch stars at K' is strongly dependent on age, the lower distance suggests that the last epoch of star formation in Maffei 1 occurred farther in the past than in these other systems. The distance and luminosity make Maffei 1 the nearest giant elliptical galaxy. In the absence of extinction, the galaxy would be among the brightest in the sky and would have an apparent size $\frac{2}{3}$ that of the full Moon. The radial velocity of Maffei 1 is $+66.4 \pm 5.0$ km s⁻¹, significantly higher than the accepted value of -10 km s⁻¹. The Hubble distance corresponding to the mean velocity of Maffei 1, Maffei 2, and IC 342 is 3.5 Mpc. Thus, it is unlikely that Maffei 1 has had any influence on Local Group dynamics.

Subject headings: galaxies: distances and redshifts — galaxies: individual (Maffei 1)

1. INTRODUCTION

Maffei 1 is a large elliptical galaxy located in the middle of the zone of avoidance ($l = 135^\circ.86$, $b = -0^\circ.55$). Unfortunately, elucidation of its fundamental properties, such as the absolute magnitude and distance, has been hampered by both its size and location. Not only is it covered with myriads of foreground stars, but it also suffers from about 5 mag of extinction in V (Buta & McCall 1983). The uncertainty in distance is especially problematic, given that it is positioned in the general direction of the Andromeda galaxy. Past work has led to the suggestion that the galaxy is near enough and moving fast enough to have been in proximity to M31 in the past 5–8 billion yr (McCall 1989; Valtonen et al. 1993). If so, it could have influenced the motions of galaxies in the Local Group, thereby invalidating the binary hypothesis of Local Group timing (Kahn & Woltjer 1959; Lynden-Bell 1981).

Because of the heavy obscuration, the existence of Maffei 1 was unknown until 1968, when Paolo Maffei discovered it on I-N and Ia-E plates acquired with the Schmidt telescope at Asiago Observatory during a search for T Tauri stars and diffuse nebulae (Maffei 1968). The subsequent flurry of research activity led to its tentative identification as an elliptical galaxy (Spinrad et al. 1971), later confirmed by Buta &

McCall (1983, 1999) and Luppino & Tonry (1993). By comparing the nuclear spectrum with spectra of the spheroid of M31 and giant ellipticals like NGC 3379, Spinrad et al. (1971) estimated A_V to be 5.2 ± 0.2 mag. Upon visual inspection of a photographic spectrum, they concluded that the velocity dispersion was “not less than 150 km sec⁻¹ or greater than 250 km sec⁻¹”; a value of 200 km s⁻¹ was adopted. Combined with a measurement of the core radius, an inferred total magnitude (11.0 mag in V) corrected for the extinction, and an assumed mass-to-light ratio, the distance was evaluated to be 1 Mpc. Consequently, it was suggested that Maffei 1 might be an unbound member of the Local Group. Certainly, the galaxy appeared to be the nearest giant elliptical.

Subsequent estimates of extinction based on studies of foreground stars indicated that the result of Spinrad et al. (1971) might be a magnitude or more too high (see Buta & McCall 1983). Buta & McCall (1983) added two new measurements. First, by measuring the $B-V$ color of the inner region via aperture photometry and comparing it with the mean color of unobscured elliptical galaxies, they estimated A_V to be 5.3 ± 0.4 mag. Also, from the total column density of gas in the direction of the galaxy, judged from both H I and CO measurements, A_V was estimated to be 4.9 ± 0.4 mag. Determinations based on analyses of foreground stars were clearly underestimates. Buta & McCall (1983) concluded that $A_V = 5.1 \pm 0.2$ mag. Through a gross extrapolation of the aperture growth curve, the apparent visual magnitude was determined to be 11.4 mag. Combining the velocity dispersion estimated by Spinrad et al. (1971) with the measurements of extinction and brightness, a distance of $2.1^{+1.3}_{-0.8}$ Mpc was derived from the relationship between

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luminosity and central velocity dispersion observed in V for elliptical galaxies, as defined by de Vaucouleurs & Olson (1982). Thus, the galaxy no longer appeared to be in the Local Group, but instead in a collection of galaxies known at the time as the Ursa Major–Camelopardalis Cloud (de Vaucouleurs 1975).

In an effort to derive a better estimate of the distance, Luppino & Tonry (1993) examined surface brightness fluctuations in K' out to a radius of $75''$. Using M32 and the spheroid of M31 as references, they concluded that the distance was 4.15 ± 0.5 Mpc. In principle, this was the best determination of distance yet. However, there were still reasons for caution, because of the possibility that the measurement of the fluctuation magnitude was compromised by contamination of the field by faint foreground stars, globular clusters in Maffei 1 itself, and variations in the galaxy-subtracted background introduced by the known dust lanes.

An even more fundamental question is whether the mix of giants in Maffei 1 responsible for the surface brightness fluctuations at K' is similar to that in either of the reference fields. One argument against this is that the fluctuation magnitude for M32 was measured to be brighter than that for M31 by 0.26 ± 0.13 mag. Also, Davidge (2001) found that the K' luminosity functions of asymptotic giant branch (AGB) stars in M31 and M32 are intrinsically different, despite the agreement in the magnitudes of their respective AGB tips. Both Luppino & Tonry (1993) and Davidge (2001) assumed that M31 and M32 are equidistant. If, in fact, the stellar mixes were identical, then surface brightness fluctuations in I would suggest that M32 is farther away than M31 by 0.15 ± 0.07 mag (Tonry et al. 2001). However, it has been demonstrated convincingly from studies of the reddening of planetary nebulae in M32 that M32 is in front of M31 (Ford, Jacoby, & Jenner 1978; Richer, Stasińska, & McCall 1999). By studying the gravitational influence of M32 on the disk of M31, Byrd (1976, 1978) concluded that M32 is only 7.5 kpc, or 0.02 mag, nearer than the nucleus of M31. Thus, the discrepancy in the fluctuation magnitudes of these two galaxies cannot be attributed to a distance effect alone.

Another problem with K' surface brightness fluctuations in Maffei 1 is the observation that the fluctuation magnitude brightens by 0.46 mag over the small range of radii studied (35% of the length of the semimajor axis of the effective isophote in I : Buta & McCall 1999). To account for this, Luppino & Tonry (1993) assumed, “not without trepidation,” that the population of stars within $24''$ was like that in M31 and that the mix from $24''$ to $75''$ was more like that in M32. $B-R$ colors within the inner arcminute of M31 and M32 differ by 0.4 mag (Peletier 1993; Walterbos & Kennicutt 1987), supporting the argument that different populations contribute to the surface brightness fluctuations observed in these galaxies. However, in Maffei 1, the photometry of Buta & McCall (1999) reveals that both $B-V$ and $V-I$ change by only 0.13 mag between the two zones in question. In other words, the stellar mix in Maffei 1 is relatively homogeneous throughout the observed region, while there is evidence that the reference field assigned to the inner observed zone differs in stellar content from the reference field assigned to the outer observed zone. The origin of some of the brightening in the fluctuation magnitude with radius in Maffei 1 may actually be globular clusters, because Buta & McCall (2003) have identified 12 candidates

between $33''$ and $75''$ in images acquired with *HST*. The more reliable determination of distance, then, might be the comparison of fluctuations within $24''$ of the nucleus with those observed in the bulge of M31. However, although the mean absolute magnitude of K' fluctuations seen in Virgo Cluster elliptical galaxies agrees with the value adopted by Luppino & Tonry (1993) for the bulge of M31, the range for five galaxies with total intrinsic $V-I$ colors like that of Maffei 1 is 1.09 mag (Jensen, Luppino, & Tonry 1996).

Using adaptive optics at the Canada-France-Hawaii Telescope, Davidge & van den Bergh (2001) were actually able to measure K' magnitudes directly for the brightest AGB stars in a $34''$ field located $6'$ from the center of Maffei 1. Interpreting the stars as being similar to the most luminous seen in the bulge of M31, they estimated a distance of $4.4^{+0.6}_{-0.5}$ Mpc. Although not entirely independent of the result of Luppino & Tonry (1993), the technique has the advantage that the luminosity of the brightest AGB stars does not appear to vary much between M32 and the bulges of M31 and the Milky Way, supporting the adoption of the AGB tip as a standard candle. However, Bressan, Chiosi, & Fagotto (1994) find a strong dependence of the luminosity of AGB stars on age. In § 7, we examine how much the age dependency may extend the range in luminosity associated with the AGB tip, and in turn, the effect on the distance to Maffei 1.

Luppino & Tonry (1993) also applied the $D_n\text{-}\sigma$ relation to arrive at an independent estimate of distance. The result, 4.2 ± 1.1 Mpc, agreed with that from surface brightness fluctuations, but the observational ingredients were highly uncertain, being founded on their surface photometry in K' (to only $90''$, i.e., 30% of D_n), an average $B-K$ color for elliptical galaxies, and the velocity dispersion of Spinrad et al. (1971). The method is reexamined in § 6 using modern data.

Distances derived from stars within Maffei 1 do not directly give information about the luminosity of the galaxy without good integrated photometry. Realizing that adequate photometry was lacking, Buta & McCall (1999) acquired images of Maffei 1 in B , V , and Cousins I , using a CCD camera attached to the Burrell Schmidt telescope at Kitt Peak. After foreground stars were carefully removed, the apparent V magnitude was found to be 11.14 ± 0.06 mag, confirming the earlier results of Spinrad et al. (1971) and Buta & McCall (1983). At the lower distance of Buta & McCall (1983), the absolute magnitude ($M_V = -20.6$) would make Maffei 1 an intermediate elliptical by the standards of galaxies in the Virgo Cluster. At the larger distance of Luppino & Tonry (1993), Maffei 1 would have a luminosity ($M_V = -22.1$) comparable to that of the brightest members of the cluster.

It is clear that there is a need to gauge the distance to Maffei 1 in a new way. As it turns out, it is also necessary to reevaluate the extinction. Since 1983, most authors have adopted the extinction to be that recommended by Buta & McCall (1983). It is behind all of the recent distance determinations described above. The map of extinction derived by Schlegel et al. (1998) from direct observations of dust emission cannot be applied because it is uncalibrated at Galactic latitudes below 5° . In fact, nobody has actually measured the extinction of Maffei 1. Rather, any evaluation of extinction has come from a measurement of the *reddening*, in combination with a reddening law and an assumption about the ratio of total to selective extinction, $R_V = A_V/E(B-V)$.

It is well known that, as a consequence of shifts in effective wavelengths, the ratio of total to selective extinction for a star depends on both the spectral energy distribution (SED) and the reddening. Until recently, the subject had never been explored for galaxies, and even for stars it had really only been investigated thoroughly for B and V . McCall & Armour (2000) and McCall (2003) have shown that the ratio of total to selective extinction for galaxies does indeed vary with morphological type, reddening, and, especially, redshift. In fact, R_V for a star-forming galaxy is different from that for a star of the same color.

In evaluating the extinction in a particular passband, most researchers use a color excess, traditionally $E(B-V)$, and a reddening law, which gives the extinction as a function of wavelength, usually normalized to $E(B-V)$. There are two problems with this approach. First, the object used to gauge the color excess does not always have the same spectrum as the object for which the extinction is desired. Second, objects used to define the reddening law may be different altogether. Even a so-called monochromatic reddening law may be normalized to a color excess defined by broadband filters, so the coefficients of the law remain object-dependent. Thus, the derivation of an extinction of a source may be filled with inconsistencies. For example, a typical researcher might use the map of Schlegel et al. (1998) to gauge the extinction of a spiral galaxy. The maps are calibrated using estimates of $E(B-V)$ for elliptical galaxies spread all over the sky (with intrinsic colors judged from the Mg_2 index). The conversion of color excesses to extinction might be accomplished using the reddening law of Cardelli, Clayton, & Mathis (1989), which is specifically founded on studies of O and B stars. In the end, a color index for elliptical galaxies is used with a reddening law for O and B stars to evaluate the extinction of a spiral galaxy!

As mentioned above, Buta & McCall (1983) gauged the color excess of Maffei 1 by two methods. The color excess judged from the comparison of the apparent $B-V$ color of the galaxy with the mean color for elliptical galaxies was converted into an extinction using $R_V = 3.5$, which was estimated from the intrinsic color and color excess via the relation derived by Olson (1975) for stars. The color excess judged from the column density of gas along the line of sight was founded on a correlation observed for O and B stars in the Milky Way. In this case, A_V was computed using $R_V = 3.2$, appropriate for those stars (Olson 1975). This second estimate of A_V really was applicable only to O and B stars, not to Maffei 1, or even to stars with the same color as Maffei 1.

For objects at high Galactic latitudes, a small error in R_V has rather insignificant consequences (except for studies of large-scale flows; see Hudson 1999). However, the error is amplified for heavily obscured objects such as Maffei 1. Properly taking into account effective wavelength shifts (McCall 2003), R_V is 3.22 for an elliptical galaxy and 3.00 for a B0 V star, given that both are at rest and obscured comparably to Maffei 1. If one uses the color excesses to solve for the optical depth along the line of sight at 1 μm (see § 5.3), the color of Maffei 1 leads to an extinction of 4.9 mag, which is 0.4 mag lower than estimated by Buta & McCall (1983), and the column density of gas gives an extinction of 4.5 mag, also 0.4 mag lower.

An additional reddening estimate was recently obtained by Davidge (2002), who measured the mean $H-K$ color of bright giants in Maffei 1 and derived $E(H-K) =$

0.28 ± 0.05 mag, based on the assumption that the brightest stars have the same intrinsic colors as M giants in Baade's window. Following the procedure described in § 5.3, this color excess leads to an extinction of 4.7 ± 0.8 mag in V . In this paper, the extinction of Maffei 1 is estimated with improved accuracy, by measuring the Mg_2 index for the first time and by deriving a value for the ratio of total to selective extinction consistent with the SED, extinction, and redshift. Then, the distance is determined for the first time from the fundamental plane using a modern measurement of the velocity dispersion in combination with the effective radius determined by Buta & McCall (1999) from wide-field surface photometry. A new determination of the radial velocity is used to evaluate the degree to which Maffei 1 departs from the Hubble flow and the likelihood of any interaction with the Local Group subsequent to the big bang.

Observations are presented in § 2, and reductions are outlined in § 3. Measurements of the Mg_2 index, velocity dispersion, and radial velocity are described in § 4. The extinction is determined in § 5, and the distance is derived in § 6. Implications for the Local Group are discussed in § 7. Finally, the properties of Maffei 1 are summarized in § 8.

2. OBSERVATIONS

All spectroscopy of Maffei 1 was carried out with the Boller & Chivens long-slit spectrograph attached to the f/7.5 focus of the 2.12 m telescope at the Observatorio Astronómico Nacional in San Pedro Mártir, Baja California, Mexico. The detector employed was a Tektronix CCD coated with Metachrome II, which consisted of 24 μm square pixels arranged in a 1024×1024 array. The readout noise was $3.0 \text{ e}^- \text{ pixel}^{-1}$, and the dark current was a negligible $0.76 \text{ e}^- \text{ pixel}^{-1} \text{ hr}^{-1}$. The readout electronics did not permit overclocking the CCD, so frames did not include overscan pixels. Consequently, to monitor the bias level, a bias exposure was taken after each target exposure. For all observations of Maffei 1, the slit was oriented at a position angle of 170° , which was close to the atmospheric dispersion direction. This was only 4° away from the minor axis of the galaxy (Buta & McCall 1999).

Low-resolution spectra suitable for measuring the Mg_2 index were obtained on 1994 December 1 UT. They were acquired in first order with a 300 lines mm^{-1} grating blazed at 5000 Å, which yielded coverage from 3450 to 7550 Å at a dispersion of 4.00 Å pixel^{-1} . To test the sensitivity of results to the aperture size, spectra were acquired with two different slit widths, 220 (2.9") and 600 μm (7.8"). The effective resolution, determined from measurements of the night-sky line [O I] $\lambda 5577$, was 2.6 pixels FWHM (10.5 Å) for the narrow-slit spectrum and 5.6 pixels FWHM (22.4 Å) for the wide-slit spectrum. The useful length of the slit was 250 pixels (3.9'). The exposures of Maffei 1 were each 1800 s long. Spectra of an HeAr arc lamp were taken at the beginning and end of the night to measure the wavelength scale. The spectrophotometric standards HD 217086, Hiltner 102, HD 84937, and G191-B2B were observed with a 600 μm slit to calibrate fluxes. To correct the data for any bias pattern and for pixel-to-pixel variations in response, nine bias exposures and three dome flat-field exposures were acquired at both the beginning and end of the night. A twilight flat-field exposure was taken at the end of the night to determine the slit illumination function.

TABLE 1
VELOCITY MEASUREMENTS

Template (1)	Type (2)	v_{\odot} (km s $^{-1}$) (3)	References (4)	v_{\odot} (Maffei 1) (km s $^{-1}$) (5)	v_{\odot} Error (km s $^{-1}$) (6)	σ_r (Maffei 1) (km s $^{-1}$) (7)	σ_r Error (km s $^{-1}$) (8)
HD 5459, first observation	G8 IV	-9.4	1, 2	63.7	14.5	184.5	17.4
HD 9166	K3 III	-13.9	3, 4	71.1	12.8	191.9	15.4
HD 5459, second observation.....	G8 IV	-9.4	1, 2	70.3	14.8	183.7	17.7
HD 22427	K2 III–IV	-31.5	5, 6	60.7	13.3	189.4	15.9
HD 27224	K1 III	-8.3	5, 7	85.5	14.2	184.3	17.1
Adopted.....	66.4	5.0	186.8	7.4

NOTE.—Col. (1): Name of template star, in order of time of observation. Col. (2): Spectral type of template star. Col. (3): Heliocentric radial velocity adopted for template star. Col. (4): References for spectral type and radial velocity. Col. (5): Heliocentric radial velocity derived for Maffei 1. Col. (6): Uncertainty in velocity of Maffei 1 (see § 4.2). Col. (7): Velocity dispersion derived for Maffei 1. Col. (8): Uncertainty in velocity dispersion of Maffei 1 (see § 4.2).

REFERENCES.—(1) Fehrenbach 1961; (2) Evans 1967; (3) Roman 1955; (4) Wilson 1953; (5) Schmitt 1971; (6) Griffin 1970; (7) Fehrenbach et al. 1987.

Spectra at high resolution appropriate for measuring the velocity dispersion (and radial velocity) were obtained on 1994 December 2 UT. They were obtained in second order with a 1200 lines mm $^{-1}$ grating blazed at 10,000 Å, which yielded a dispersion of 0.50 Å pixel $^{-1}$. The tilt was set so that spectra spanned 5120–5630 Å. A BG39 order-blocking filter was used to exclude light from first order. The slit width was set to 270 μm (3''.5), which mapped onto 1.4 pixels (0.7 Å). In other words, the slit was undersampled. Measurements of night-sky [O I] λ5577 revealed that the effective resolution on average was 2.03 pixels FWHM (1.05 Å). To improve the signal-to-noise ratio, pixels *along the slit* were on-chip binned in groups of four.

High-resolution observations were made in a manner designed to maximize velocity precision. Seven 1200 s exposures of Maffei 1 were acquired, each bracketed by observations of an HeAr arc lamp. Template spectra were provided by four G and K giants with known radial velocities and positions in the sky comparable to that of Maffei 1, all selected from the Bright Star Catalogue Supplement (Hoffleit, Saladyga, & Wlasuk 1983). Relevant data are summarized in Table 1. The stars were observed, bracketed by arc exposures, before, between, and just after the Maffei 1 exposures, with exposure times ranging from 30 to 40 s. One giant was observed twice to check repeatability. Since the orientation of the slit was almost north-south (the direction of atmospheric dispersion for Maffei 1), errors in tracking and guiding would have moved the stars perpendicular to the slit, in essence helping to fill the slit comparably to the nucleus of Maffei 1. After completing the observations, five dome flat-field exposures were taken. No twilight flat was acquired. No flux standards were observed.

To compare the properties of Maffei 1 with those of more distant galaxies, it is necessary to correct measurements to a common physical scale. Thus, the slit width and the length of extraction apertures must be converted to angular units. From the telescope parameters, the scale at the slit was computed to be 12''.97 mm $^{-1}$. The scale along the spatial direction at the detector had to be measured. A spectrum of a field in the galaxy UGC 4115, which was acquired on 1994 November 30 UT with the same low-resolution configuration as used for Maffei 1, was suitable for this purpose, as it included an *HST* GSC star and a compact H II region of known separation (Kingsburgh & McCall 1998). Also, the slit used for the low-resolution observations of Maffei 1 the

following night admitted the light from four stars that were well separated from the core of the galaxy and whose positions were known precisely in *V* (Buta & McCall 1999). From these data, the scale along the slit was determined to be 0''.925 pixel $^{-1}$.

3. REDUCTIONS

Reductions were carried out completely within IRAF.⁴ Each night was reduced independently. The mean bias level of each image of a source was judged from the bias frames taken closest in time and then subtracted. Compensation for pixel-to-pixel variations in the bias was achieved by subtracting a zero-level correction frame constructed by averaging all of the median-subtracted bias images taken during the night. To correct for pixel-to-pixel variations in response, a master dome flat was created by averaging all bias-corrected dome flat-field images.

Subsequent reductions of the low-resolution spectra proceeded as follows. First, the master dome flat was rectified. The twilight flat was used to derive a smooth illumination function describing how the response varied along the slit. Flat-field corrections were accomplished by dividing the product of the master dome flat and the illumination function into each source image. Dispersion solutions in two dimensions were separately derived for the arc spectra taken at the beginning and end of the night and then averaged using FITCOORDS. Curvature along the dispersion direction was traced using spectra of standard stars and extragalactic H II regions displaying a strong continuum. Finally, spectra of targets were transformed to linear wavelength and spatial scales via TRANSFORM. One-dimensional versions of the target spectra were extracted using APALL.

Each one-dimensional spectrum of Maffei 1 was created by summing without weights the 20 rows (18''.5) in which the signal was noticeably above the background. The background signal was determined using sampling windows on either side, 20 rows (18''.5) each in width. The innermost boundary of each window was located 30 rows (27''.8) from the midpoint of the galaxy signal. The proximity of these

⁴ IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA), Inc., under contract to the National Science Foundation.

windows to the center of the galaxy was necessitated by the complexity of the slit profile. A linear fit to the median signal within each background window was used to produce the background-subtracted spectra. Based on the surface brightness profile of Buta & McCall (1999), the flux from the galaxy contributing to the signal in the background windows is 5.9% of that at the center. In § 4.1, we evaluate the degree to which this affects our measurement of the Mg_2 index and derive an appropriate correction.

The sensitivity function was computed by simultaneously fitting the spectra of HD 217086, Hiltner 102, and HD 84937. The spectrum of G191-B2B was excluded because of anomalous residuals. Then the spectra of Maffei 1 were converted to a flux scale with the aid of CALIBRATE. Mean extinction coefficients for San Pedro Martir were employed throughout (W. Schister 1997, private communication).

Reductions of the high-resolution spectra after preprocessing proceeded somewhat differently. The master dome flat was flat enough to divide directly into the source spectra without it having to be rectified. Dispersion solutions for each of the five template spectra and each of the seven spectra of Maffei 1 were derived from the HeAr arc spectra bracketing them. Each spectrum was traced individually and then, with the appropriate dispersion solution, transformed to linear spatial and wavelength scales. Fits to the night-sky line [O I] $\lambda 5577$ revealed outstanding stability in both wavelength and focus. Over the seven spectra of Maffei 1, the wavelength of the line varied by only $\pm 0.05 \text{ \AA}$ ($\pm 3 \text{ km s}^{-1}$), and the FWHM was stable to $\pm 0.02 \text{ \AA}$ ($\pm 1 \text{ km s}^{-1}$). Spectra of Maffei 1 and the template stars were shifted (by up to 0.13 \AA) to force the wavelength of the [O I] line to a common value, specifically, 5577.35 \AA (Bowen 1960). Then, one-dimensional versions were extracted using APALL by averaging with signal-dependent weights the eight rows ($29''.6$) centered on the peak flux from the source. The choice of window was driven by the extent of detectable flux in the Maffei 1 spectra. The background was defined by two windows roughly $1'$ wide centered approximately $65''$ away on either side of the nucleus of the galaxy. Finally, an unweighted average of the seven one-dimensional spectra of Maffei 1 was computed to arrive at the spectrum used for measuring the velocity dispersion and radial velocity. This spectrum is compared with that of one of the template stars in Figure 1. The signal-to-noise ratio of the Maffei 1 spectrum is about 25 pixel^{-1} .

4. MEASUREMENTS

4.1. Mg_2 Index

The Mg_2 index is a measure of the deficit of flux at the MgH and Mg *b* absorption features relative to the continuum level defined by neighboring spectral regions (see § 2 of Worthey et al. 1994). For unobscured elliptical galaxies, it is correlated with color (see § 5.1). Consequently, it can be used to judge the intrinsic color of a reddened elliptical galaxy.

The low-resolution spectrum of Maffei 1 from which the Mg_2 index was determined is shown in Figure 2, with the feature and continuum sampling bands marked. In measuring the index, we followed Hudson (1999) and adopted the rest-frame values defining the feature and continuum bands to be those recommended by Burstein et al. (1984). This ensures consistency with the Mg_2 indices used to construct

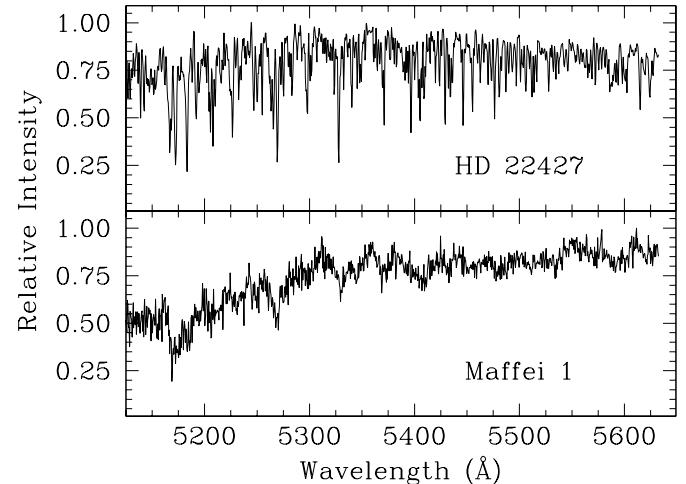


FIG. 1.—High-resolution spectra of Maffei 1 (bottom) and the K2 giant HD 22427 (top), one of four template stars used to measure the radial velocity and velocity dispersion. The Mg_2 absorption feature can be clearly seen at $5155\text{--}5198 \text{ \AA}$.

the color- Mg_2 relation from which we determine the reddening (§ 5.1). Measurements were made using IRAF's SPLOT module, which computes the equivalent width of a spectral feature by taking the sum of the continuum-subtracted pixels between the two wavelengths defining the feature. The continuum was determined by drawing a straight line defined by the wavelength midpoints of the surrounding continuum bands and the mean flux within each continuum band. The continuum level at the feature was taken to be the interpolated flux at the midpoint of the feature bandpass. The error in the continuum level was computed as the average standard error of the mean flux measured within the blue and red continuum bands. From the wide-slit spectrum, $Mg_2 = 0.305 \pm 0.049 \text{ mag}$, and from the narrow-slit spectrum, $Mg_2 = 0.312 \pm 0.065 \text{ mag}$. The uncertainty in each measurement is computed from the standard error in the equivalent width, for which the error in the line flux is the average of the 3σ errors in the fluxes measured in the blue and red continuum bands, and the error in the continuum level is as described above.

Significant variations in the focus with wavelength can change how light is distributed perpendicular to the dispersion, thereby adding uncertainty to measurements of the Mg_2 index at small radii (see Fisher, Franx, & Illingworth 1995). To determine the extent to which our measurements suffer from this effect, we examined the FWHM as a function of wavelength of the spectrum of a foreground star on the images containing the Maffei 1 spectra. The width of the star remained constant to within 0.2 pixels ($0''.2$) over the wavelength range encompassing the Mg_2 feature and the two surrounding bands used to define the continuum level. Since the spectra were produced by integrating the light from the galaxy over 20 pixels, the degree to which focus instability contributes to the uncertainty in our Mg_2 measurements is effectively negligible.

Our observations of the spectroscopic standard HD 84937 can be used to judge how close our measurements of the Mg_2 index of Maffei 1 are to the Lick Image Dissector Scanner (Lick-IDS) system, on which measurements of the reference galaxies are placed. Burstein et al. (1984) normalized all galaxy spectra by scans of a quartz-iodide

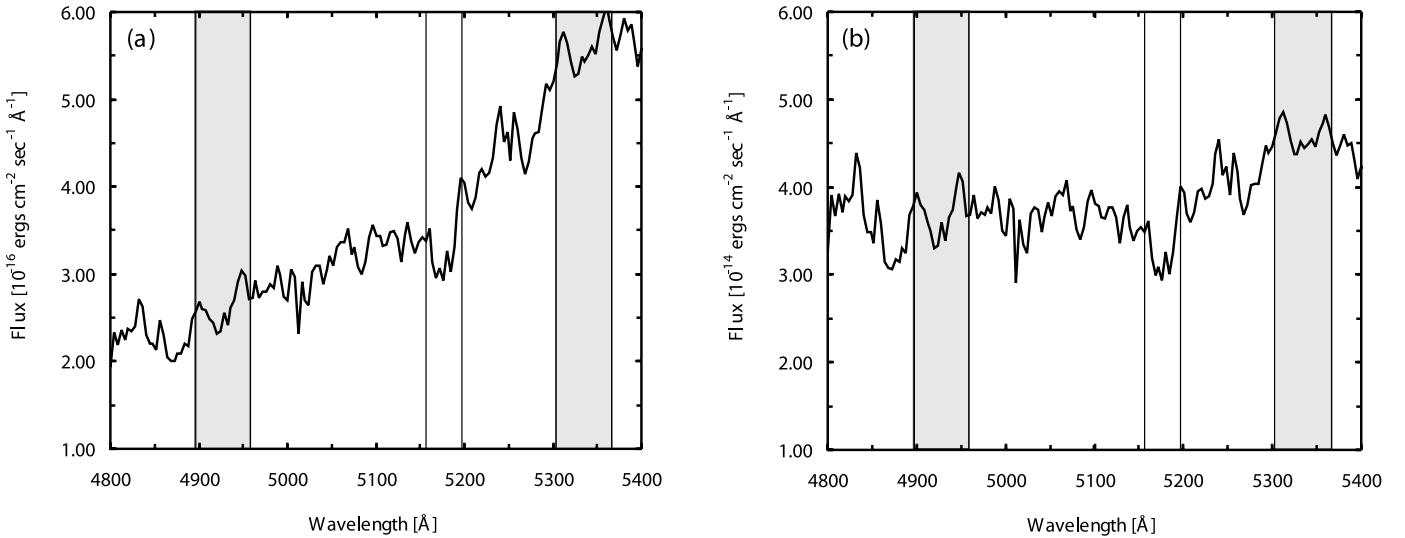


FIG. 2.—(a) Observed and (b) reddening-corrected narrow-slit spectra of Maffei 1. The central region marks the boundaries of the Mg₂ absorption feature. The continuum level is defined by the mean flux within the blue and red bands marked by the outer shaded regions. The reddening-corrected spectrum illustrates what would be observed if Maffei 1 were reddened, on average, as much as the comparison ellipticals (see § 5.2).

tungsten lamp but did not place them on a flux scale. Our low-resolution spectrum of HD 84937 with the highest signal-to-noise ratio was obtained on the night of 1994 December 2 UT. We used this spectrum to measure the Mg₂ index as well as the equivalent widths of the Mg *b* and H β features. The measurements were made using the same procedures adopted by Worthey et al. (1994). The observed resolution (10.1 Å) is comparable to the value of 8 Å reported by Worthey et al. (1994). Our results are 0.012 ± 0.006 mag for the Mg₂ index, 0.41 ± 0.14 Å for the equivalent width of the Mg *b* feature, and 3.63 ± 0.35 Å for the equivalent width of H β . In comparison, the Lick-IDS values obtained by Worthey et al. (1994) are 0.024 ± 0.008 mag, 0.50 ± 0.23 Å, and 3.49 ± 0.22 Å for the Mg₂, Mg *b*, and H β features, respectively. We conclude that our measurements can be considered to be consistent with those of the Lick-IDS system, despite the differing approaches to flux calibration.

From the *V*-band surface brightness profile of Buta & McCall (1999), the surface brightness of the galaxy at the radius of the background sampling windows has dropped to 3.5% of that in the center. The degree to which this affects our measurement of the Mg₂ index can be estimated from

$$(Mg_2)_0 = (Mg_2)_{\text{obs}} + 2.5 \log[(1 - k_l)/(1 - k_c)], \quad (1)$$

where $(Mg_2)_{\text{obs}}$ is the measured Mg₂ index, $(Mg_2)_0$ is the Mg₂ index that would be measured if there were no galaxy signal in the background regions, and k_l and k_c are the ratios of the surface brightness of the galaxy at the midpoint of the background regions to the surface brightness at the center of the galaxy in the line and continuum, respectively. If the strength of the Mg₂ feature did not vary with radius, the observed Mg₂ index would be equivalent to the true Mg₂ index. However, gradients in Mg₂ are known to exist; Davies, Sadler, & Peletier (1993) found the mean of the radial gradients in Mg₂ for ellipticals to be -0.059 mag per normalized radius r/r_e^* , where r is the radius at which the Mg₂ index is measured and r_e^* is related to the effective radius r_e of the circular aperture encompassing half of the total light of the galaxy in *B*. We use this result to find the

expected change in the Mg₂ index from the core of Maffei 1 out to the midpoint of the background windows ($37''$). For line indices measured along the minor axis, as is the case for our Mg₂ measurement, the normalization factor, r_e^* , is given by $r_e(1 - \epsilon)^{1/2}$, where ϵ is the ellipticity. Since $r_e = 222''$ and $\epsilon = 0.271$ (Buta & McCall 1999), then $r/r_e^* = 0.19$. The change in the Mg₂ index from the center of Maffei 1 to r/r_e^* is therefore expected to be -0.011 mag. We compute $k_l/k_c = 1.011$, given that the change in the Mg₂ index is equal to $-2.5 \log(k_l/k_c)$. From the *V*-band surface brightness profile of Buta & McCall (1999), $k_c = 0.059$, so $k_l = 0.060$. By equation (1), the magnitude of the correction to the observed Mg₂ index is therefore -0.001 mag. The corrected indices are 0.304 ± 0.049 and 0.311 ± 0.065 mag for the wide- and narrow-slit spectra, respectively.

The centers of the two continuum bands are 407 Å apart. Thus, for heavily reddened galaxies, the Mg₂ index can be affected by differential extinction. In the case of Maffei 1, the blueward band is extinguished by roughly 0.6 mag more than the redward band (compare Fig. 2a with Fig. 2b). In § 5.2, we employ an iterative process to arrive at the Mg₂ index that would be measured if Maffei 1 were reddened comparably to the reference galaxies defining the (*V*–*I*)–Mg₂ relation.

4.2. Radial Velocity and Velocity Dispersion

The radial velocity of Maffei 1 was measured by cross-correlating the spectrum of the galaxy with each of the five template spectra. This was accomplished using the task XCSAO in the package RVSAO of IRAF (see Tonry & Davis 1979). To avoid contamination by night-sky [O I] $\lambda 5577$, and to improve the signal-to-noise ratio of the cross-correlation peak, analyses were restricted to the wavelength range 5125–5570 Å, which is where absorption lines are strongest and most numerous.

The results for the heliocentric velocities are given in column (5) of Table 1. The sign of the velocities was confirmed by visual inspection. The errors in column (6) are those generated by XCSAO according to the algorithm derived in

Tony & Davis (1979). The result from HD 27224 is clearly deviant with respect to the other four measurements, so it is rejected. We suspect that the radial velocity of this star is errant. Thus, the heliocentric velocity of Maffei 1 is adopted to be the unweighted average of the other four values. Their outstanding agreement confirms that offsets caused by variations in the filling of the slit are small. The uncertainty in the radial velocity of Maffei 1 is adopted to be the standard deviation of the different determinations, excluding HD 27224, as opposed to the least-squares error (i.e., that derived from the inverse sum of the squares of the uncertainties in the individual measurements). Since the standard deviation encompasses the uncertainty in the radial velocities of the template stars as well as the XCSAO fitting uncertainty, whereas the least-squares error only reflects the latter, it is likely that the standard deviation is a more realistic estimate of the uncertainty. We note that the least-squares error is only 1.9 km s^{-1} larger than the adopted error.

The heliocentric radial velocity of Maffei 1 is $+66.4 \pm 5.0 \text{ km s}^{-1}$, which is significantly higher than previously thought. For their simulations of the dynamical evolution of the Local Group, Valtonen et al. (1993) adopted a value of -10 km s^{-1} , which was the “mean” tabulated by Huchtmeier & Richter (1986). Its origin was a photographic measurement by Spinrad et al. (1971), who estimated the uncertainty to be 50 km s^{-1} . Buta & McCall (1999) quoted a velocity of -87 km s^{-1} , which was derived from preliminary versions of the spectra presented here and analyzed using the Fourier quotient technique (Kormendy 1988). However, the sign was incorrectly established, and the magnitude was affected by an inferior wavelength calibration. Clearly, the new result has significant implications for dynamical timing and especially conclusions about the relevance of Maffei 1 to motions in the Local Group.

The velocity dispersion of Maffei 1 was also measured by cross-correlating the spectrum of the galaxy with each template spectrum using the XCSAO task. As was the case for the determination of the radial velocity, the spectral range was restricted to the 890 pixels in the range 5125–5570 Å, particularly because the overwhelming majority of the “power” in absorption lines was blueward of [O I] $\lambda 5577$. Experiments showed that both wider and narrower ranges led to more scatter in the results (although the mean hardly changed). The continuum was removed from all spectra before processing. Ends of the spectra were windowed with a 5% cosine bell. Changes in the width of this bell had little effect on the results. Low- and high-frequency noise were filtered using a cosine bell with a cut-on from 5 to 20 and a cutoff from 150 to 400. The latter two values were determined graphically from the power spectrum. Of the four values, only the last had any significant effect on the results, and then only if a wildly discrepant choice were made.

The results for the velocity dispersions are given in column (7) of Table 1. All determinations are in excellent agreement. Thus, the velocity dispersion of Maffei 1 is adopted to be their unweighted average, namely, $186.8 \pm 7.4 \text{ km s}^{-1}$. Tony & Davis (1981) found that when the velocity dispersion is much larger than the dispersion in the line-spread function, the uncertainty in the velocity dispersion is $1.2\delta v_{\odot}$, where δv_{\odot} is the uncertainty in the heliocentric radial velocity. We adopted this result to compute the uncertainties in the velocity dispersions given in column (8) of Table 1. Conservatively,

we adopt the uncertainty in the velocity dispersion of Maffei 1 to be the least-squares error.

Interestingly, the estimate of Spinrad et al. (1971) was close to the right answer. At the time, this led to the conclusion that Maffei 1 was located at the edge of the Local Group. However, it will be shown that our knowledge of the fundamental plane today leads to a very different conclusion.

Spinrad et al. (1971) also noted a discontinuity in spectral lines through the nucleus and estimated a rotational velocity of 130 km s^{-1} averaged over $30''$. The position angle of the slit employed was not identified, but it might be presumed to have been along the major axis. There is no evidence of a discontinuity in the two-dimensional version of our combined spectrum, which was taken along the minor axis, although it is possible that on-chip binning reduced the spatial resolution enough to hide it.

4.3. Aperture Corrections

Both the Mg₂ index and the velocity dispersion vary across the face of an elliptical galaxy. Thus, to compare measurements for Maffei 1 with those for other galaxies, as must be done to derive the reddening and distance, the measured values must be adjusted to a common standard aperture.

Jørgensen et al. (1995) derived an empirical aperture correction formula for velocity dispersions as a function of the equivalent angular radius θ_{obs} of an observing aperture normalized to the angular radius θ_e of the effective aperture of the galaxy, i.e., the circular aperture enclosing half of the total light in B . While their adopted power-law fit is adequate for typical galaxies, it deviates considerably from their empirical data in the region $\log(\theta_{\text{obs}}/\theta_e) \leq -1.4$, which is where a nearby giant object like Maffei 1 resides. A better fit to the data points in this region is given by

$$\log(\sigma_{e8}/\sigma_{\text{obs}}) = 0.032 \log[\theta_{\text{obs}}/(\theta_e/8)], \quad (2)$$

where σ_{e8} is the “standard” velocity dispersion that would be measured through an aperture with a radius of $\frac{1}{8}$ of the radius of the effective aperture of the galaxy, σ_{obs} is the observed velocity dispersion measured through an aperture of width x and length y , and θ_{obs} , the equivalent aperture radius, is given by $1.025(xy/\pi)^{1/2}$. Davies et al. (1993) found that the radial gradient in Mg₂ is similar to that in the velocity dispersion, so equation (2) can be used to correct an Mg₂ index, too, simply by replacing $\log \sigma$ with Mg₂.

The radius of the effective aperture of Maffei 1 in B is $222''$ (Buta & McCall 1999). Based on the angular scales along and perpendicular to the slit (§ 2), the aperture dimensions for the two low-resolution spectra and the high-resolution spectrum are $2''.85 \times 18''.50$, $7''.78 \times 18''.50$, and $3''.50 \times 29''.60$, respectively. The equivalent aperture radii for the two low-resolution spectra and the high-resolution spectrum are therefore $4''.20$, $6''.94$, and $5''.89$, respectively. The aperture-corrected velocity dispersion is $180.0 \pm 7.4 \text{ km s}^{-1}$, with all of the uncertainty coming from the measurement of the velocity dispersion itself, owing to the small size of the aperture correction. For the Mg₂ indices, the aperture corrections for both the wide- and narrow-slit spectra amount to 0.03 mag. We note that this is consistent with the change in the Mg₂ index implied by the small change in $V-I$ between the equivalent aperture radii and θ_e . Based on the observations of Buta & McCall (1999), the changes in $V-I$

from $4''.20$ to θ_e (narrow-slit) and from $6''.94$ to θ_e (wide-slit) imply changes in the Mg_2 index of 0.036 ± 0.006 and 0.032 ± 0.006 mag, respectively, according to the $(V-I)$ - Mg_2 relation given by equation (3) (see § 5.1). The agreement between the aperture corrections derived from equation (2) and the declines in Mg_2 predicted from the changes in $V-I$ confirms the applicability of our correction scheme based on the empirical correction data of Jørgensen et al. (1995). Since the reference Mg_2 indices were aperture-corrected using the data of Jørgensen et al. (1995), we adopt for consistency the aperture correction given by equation (2) for Maffei 1, namely, 0.03 mag.

5. EXTINCTION

5.1. The $(V-I)$ - Mg_2 Relation

Bender, Burstein, & Faber (1993) showed that for all dynamically hot systems, the $B-V$ color is tightly correlated with the Mg_2 index. Any scatter in the relationship appears to be random, i.e., not tied to another parameter. In principle, then, it is a useful tool for evaluating the intrinsic color of an obscured galaxy and, in turn, the reddening, as was done by Schlegel et al. (1998).

Unfortunately, because of the heavy obscuration, the properties of Maffei 1 in B remain considerably more uncertain than in V or I . It is productive, therefore, to seek out a relationship between $V-I$ and the Mg_2 index. Hudson (1999) summarizes a large set of measurements of the Mg_2 index for elliptical galaxies, including the extensive collection of Faber et al. (1989), but all homogenized to the system of Burstein et al. (1984), which was developed at Lick Observatory with the Lick-IDS system. For 97 of the galaxies, effective and total photoelectric $V-I$ colors have been determined by Buta & Williams (1995). The effective $V-I$ color, defined as the integrated color within the circular aperture transmitting half the total blue light, is preferred over the total color, as the latter is derived by extrapolation and generally has a lower precision as a result. Aperture corrections were applied to the Mg_2 indices using equation (2) of Jørgensen et al. (1995). The colors were corrected for reddening by deriving the optical depth at $1\text{ }\mu\text{m}$ from the $B-V$ color excesses provided by Schlegel et al. (1998) (the precise method is described in § 5.3). K -corrections were derived from the same SED used to evaluate the redshifts. As shown in Figure 3, the data reveal a tight correlation between the corrected effective $V-I$ color, designated by $(V-I)_e^0$, and the corrected Mg_2 index. A linear least-squares fit gives

$$(V-I)_e^0 = (1.05 \pm 0.10)Mg_2 + (0.85 \pm 0.03) . \quad (3)$$

The rms scatter is only 0.04 mag. For the same galaxies, the relation between the total $V-I$ color and the Mg_2 index displays a much higher rms scatter of 0.09 mag. In comparison, the effective $B-V$ color, $(B-V)_e^0$, varies with Mg_2 as

$$(B-V)_e^0 = (0.93 \pm 0.06)Mg_2 + (0.64 \pm 0.02) . \quad (4)$$

Within errors, the slope is consistent with that found for the relation between $(V-I)_e^0$ and Mg_2 . Thus, for a given uncertainty in Mg_2 , $(V-I)_e^0$ can be judged just as well as $(B-V)_e^0$. The rms is less, however, being only 0.02 mag. It is possible that the $V-I$ measurements employed in determining $(V-I)_e^0$ are inherently more uncertain than the data that

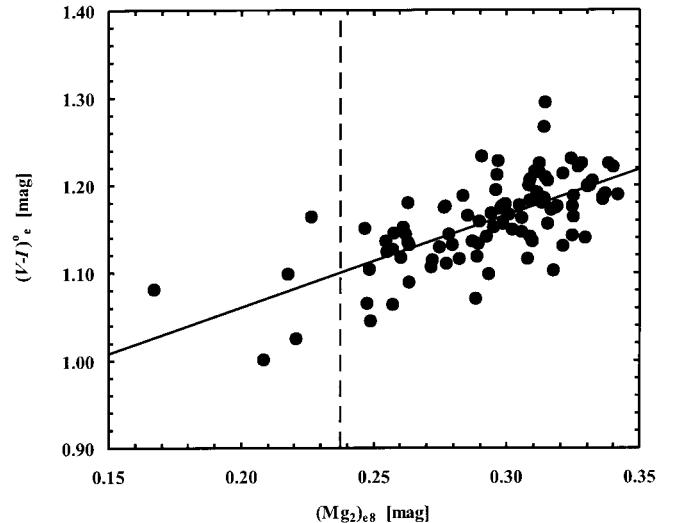


FIG. 3.—Relationship between effective $V-I$ color and Mg_2 index for elliptical galaxies. The solid line marks the linear least-squares fit. The rms scatter in $(V-I)_e^0$ is 0.04 mag. The dashed line marks the Mg_2 index of Maffei 1.

went into determining $(B-V)_e^0$ because of the difficulties associated with doing photoelectric photometry in I .

5.2. Reddening Correction for the Mg_2 Index

As mentioned in § 4.1, a measurement of the Mg_2 index from the spectrum of Maffei 1 is not directly comparable with the Mg_2 indices used to define the $(V-I)$ - Mg_2 relation, as the reference Mg_2 indices were determined from spectra that are reddened to a much lesser degree than that of Maffei 1. To bring each Mg_2 index for Maffei 1 on to the same scale as the comparison Mg_2 indices, we obtained a first approximation of the reddening of Maffei 1 using equation (3) with the Mg_2 index measured from the reddened spectrum. Next, we used this first approximation to produce an unextinguished spectrum. The unextinguished spectrum was then extinguished using the average reddening of the comparison ellipticals. The Mg_2 index measured from this spectrum is therefore on the same scale as the Mg_2 indices used to define the $(V-I)$ - Mg_2 relation. The revised value was inserted into equation (3), from which we obtained a second approximation of the reddening of Maffei 1. This process was repeated until each Mg_2 index converged. Our final aperture-corrected values are 0.232 ± 0.040 mag for the wide-slit spectrum and 0.238 ± 0.061 mag for the narrow-slit spectrum. Thus, the reddening corrections lowered the Mg_2 indices by 0.05 mag, which is almost twice the effect of the aperture corrections. We note that the corrected values are nearly identical to the “true” Mg_2 indices, i.e., the line strengths we would measure if the galaxy were completely unobscured, which are 0.231 and 0.237 mag for the wide- and narrow-slit spectra, respectively. This indicates that the extinction of the comparison elliptical galaxies is small enough that the shape of their continua in the proximity of the Mg_2 feature is not noticeably altered by reddening.

To determine the intrinsic $V-I$ color of Maffei 1 from equation (3), we adopt the Mg_2 index measured from the narrow-slit spectrum, namely, 0.238 ± 0.061 mag, as opposed to the value obtained from the wide-slit spectrum. The reason for this is that the spectral resolution of the narrow-slit spectrum ($10.5\text{ }\text{\AA}$) is comparable to the spectral

resolution of the Lick-IDS system (9 Å) on which the Mg₂ indices used to construct the color-Mg₂ relation are based. We note that the spectral resolution of the wide-slit spectrum is over twice as poor as that of the narrow-slit spectrum, yet the Mg₂ indices obtained from the two spectra are in close agreement, differing by only 0.006 mag. This indicates that the measurement of the Mg₂ index is not strongly dependent on spectral resolution within the range of resolutions in our observations.

5.3. The Extinction of Maffei 1

From equation (3), the fully corrected Mg₂ index obtained from the narrow-slit spectrum of Maffei 1 implies $(V-I)_e^0 = 1.100 \pm 0.065$ mag. Adopting $(V-I)_e = 3.12 \pm 0.05$ mag (Buta & McCall 1999), we obtain $E(V-I) = 2.020 \pm 0.082$ mag. As well, equation (4) gives $(B-V)_e^0 = 0.864 \pm 0.057$ mag. Since $(B-V)_e = 2.42 \pm 0.08$ (Buta & McCall 1999), then $E(B-V) = 1.555 \pm 0.098$ mag.

The measured color excess can be used to judge the extinction in any passband, provided that appropriate account is taken of the shifts in effective wavelength as a function of source morphology, reddening, and redshift. McCall & Armour (2000) and McCall (2003) have developed procedures for doing so. First, a monochromatic extinction curve appropriate for the diffuse interstellar medium, which is primarily responsible for obscuring extra-galactic sources, must be adopted. 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 (McCall & Armour 2000). The reddening law chosen to evaluate the extinction of Maffei 1 is that given by the algorithm of Fitzpatrick, which, when applied to the spectrum of Vega, yields $R_V = 3.07$ after integration of the flux passed by response curves characterizing B and V filters.

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 of a source in any passband by applying the appropriately scaled reddening law to the spectrum and integrating through the response function for the filter. The best choice of wavelength is 1 μm, because it is in a part of the reddening law that is not very sensitive to environment, and because the optical depth there is comparable numerically to $E(B-V)$. The optical depth at 1 μm, τ_1 , can be computed from any color excess by an iterative process. First, a value for τ_1 is guessed, and the spectrum of the source is extinguished with the aid of the scaled reddening law. For each broadband filter Λ used to compute the color excess, the ratio R_Λ^1 of the total extinction A_Λ to the optical depth τ_1 is determined by integrating the spectrum transmitted by the response curve for the filter. Then, the value of τ_1 is revised and the process repeated. Convergence is generally rapid.

To determine τ_1 for Maffei 1, McCall (2003) created a truly integrated SED for a typical unreddened elliptical galaxy extending all the way from 0.13 to 3.8 μm. This was accomplished by combining spectra and photometry available for NGC 3379. The spectrum was shifted to the redshift of Maffei 1 and then iteratively reddened until the observed value of the color excess for Maffei 1 was reproduced. Filter response curves were adopted from Bessell (1990). In the

case of $E(V-I)$, the analysis converged on a value of τ_1 equal to 1.69 ± 0.07 , which leads to $A_V = 4.67 \pm 0.19$ mag. Note that the error here does not include that in the zero point of the reddening law (i.e., R_V for Vega). In comparison, $E(B-V)$ yields an optical depth of 1.82 ± 0.11 , from which $A_V = 5.01 \pm 0.32$ mag. These values are consistent with the results from $E(V-I)$, justifying the choice of reddening law. However, because of the added uncertainty in the photometry in B , the errors are twice as great. For this reason, along with the fact that the Galactic reddening law is more sensitive to environment in the ultraviolet, we choose to adopt for τ_1 the value derived from $E(V-I)$ alone. The corresponding values of R_Λ^1 and A_λ for B , V , and I (Cousins) are given in Table 3.

If instead the nonmonochromatic reddening law of Cardelli et al. (1989) is employed [parameterized as before to deliver $A_V/E(B-V)$ equal to 3.07 for Vega], then $E(V-I)$ and $E(B-V)$ lead to values of τ_1 equal to 1.84 and 2.06, respectively. The two values are significantly more discrepant than those derived using the law of Fitzpatrick (1999). The implied difference in A_V amounts to 0.6 mag, as against 0.3 mag based on the analysis with the Fitzpatrick law.

Our adopted extinction for Maffei 1 in V is 4.67 ± 0.19 mag. This is consistent with the estimate of Davidge (2002), which, after corrections for effective wavelength shifts (in the manner described for Maffei 1, but with the aid of the spectrum of a M0 III star), leads to $A_V = 4.7 \pm 0.8$ mag. Our result is also consistent with that required by the column density of gas along the line of sight, which is $A_V = 4.5 \pm 0.4$ mag after correction for effective wavelength shifts using the spectrum of a B0 V star. It is 0.2 mag less than demanded by the $B-V$ color comparison of Buta & McCall (1983), which, after correction for effective wavelength shifts, is $A_V = 4.9 \pm 0.2$ mag.

6. DISTANCE

Until the late 1980s, distances to elliptical galaxies were judged from the Faber-Jackson relation, which correlated an elliptical galaxy's luminosity with its velocity dispersion. Unfortunately, the scatter in the Faber-Jackson relation was at least twice that of the Tully-Fisher relation for spiral galaxies, on the order of 0.8 mag in M_B . However, independent studies by Djorgovski & Davis (1987) and Dressler et al. (1987) revealed that the addition of the surface brightness as a third parameter considerably tightened the relation. This led to the realization that elliptical galaxies are confined to a plane, called the fundamental plane (FP), in a three-dimensional space defined by coordinates linked to mass, density, and the mass-to-light ratio. One way of describing the FP is through the relationship among the metric effective radius R_e , the velocity dispersion σ , and the mean surface brightness $\langle J \rangle_e$ within R_e :

$$R_e \propto \sigma^\alpha \langle J \rangle_e^{-\beta}. \quad (5)$$

Independent determinations of the power-law exponents for different passbands have found $\alpha = 1.2-1.4$ and $\beta = 0.7-0.9$, with no obvious trend of the coefficients with wavelength. This form of the FP is adopted to evaluate the distance to Maffei 1.

Because of the reduced extinction and the availability of wide-field surface photometry, the appropriate passband to use to derive an FP distance to Maffei 1 is I . Unfortunately,

the FP has never been constructed in this passband. We do so here, using spectroscopy and I -band photometry obtained by Scoggio, Giovanelli, & Haynes (1998a, 1998b, hereafter SGHa, SGHb, respectively) for a sample of 17 elliptical galaxies in the Coma Cluster. The Coma Cluster is ideal for an FP analysis, as its large distance minimizes scatter due to the varying depths of galaxies within the cluster. Various independent studies validate the assumption that the FP in this distant realm has the same size and shape as that for nearby clusters (Jørgensen, Franx, & Kjærgaard 1996; Kelson et al. 2000). Furthermore, de la Rosa, de Carvalho, & Zepf (2001) find no dependency of the FP on environment, based on a comparison of ellipticals in compact groups with a sample of ellipticals in the field or in very loose groups.

For the distance to Coma, we adopt 78.8 Mpc. This is the average value measured from the FP in Gunn r and from the Tully-Fisher relation in I (which are consistent within 0.2 Mpc; see Freedman et al. 2001), but anchored to the maser distance of NGC 4258 (7.2 Mpc; Herrnstein et al. 1999), rather than to the Cepheid distance of the LMC (see Freedman et al. 2001).

The elliptical galaxy sample is given in Table 2. Great care was taken to correct observables in the same manner as for Maffei 1. After first transforming effective radii to effective aperture radii following the prescription of Olson & de Vaucouleurs (1981), velocity dispersions were corrected to the standard aperture using equation (2) of Jørgensen et al. (1995), which is appropriate for $-1.4 \leq \log(\theta_{\text{obs}}/\theta_e) \leq -0.5$. Extinctions were estimated by extracting $E(B-V)$

from the maps of Schlegel et al. (1998) and then deriving τ_1 iteratively using the SED of an elliptical galaxy. Surface brightnesses were corrected for the K -effect and $(1+z)^4$ dimming, the former determined from the same SED used to arrive at τ_1 . In an effort to lessen scatter due to varying orientations, surface brightnesses were also multiplied by the axis ratio q derived from $\log R_{25}$ in B (de Vaucouleurs et al. 1991; RC3). For true oblate spheroids, this reduces surface brightnesses to the values that would be seen if the galaxies were observed face-on.

The I -band FP for the Coma sample is plotted in Figure 4. Note that R_e is the metric length in kiloparsecs of the semimajor axis of the elliptical isophote encompassing half of the total light in I (the effective isophote), σ_{e8} is the aperture-corrected velocity dispersion in units of km s^{-1} (see § 4.3), and $\langle \mu \rangle_e^0$ is the fully corrected estimate for the mean face-on surface brightness within R_e in units of mag arcsec^{-2} (see Table 2). Values of $\langle \mu \rangle_e^0$ were derived from the surface brightness of the effective isophote, μ_e , and values of R_e were calculated from the length of the semimajor axis of that isophote, r_e . Both r_e and μ_e were measured by fitting free ellipses to the surface brightness profiles. A linear least-squares fit to the data gives

$$\log R_e = (0.87 \pm 0.19) \log \sigma_{e8} + (0.83 \pm 0.06) \langle \mu \rangle_e^0 / 2.5 - (7.79 \pm 0.69) . \quad (6)$$

The rms scatter in the relation is 0.09 in $\log R_e$, as against 0.11 when the axis ratio correction is excluded. The fit to the

TABLE 2
FUNDAMENTAL PLANE PARAMETERS

Galaxy (1)	v_\odot (km s $^{-1}$) (2)	b/a (3)	r_e (arcsec) (4)	θ_e (arcsec) (5)	$\langle \mu \rangle_e$ (mag arcsec $^{-2}$) (6)	A_I^{gal} (mag) (8)	A_I^c (mag) (9)	$\langle \mu \rangle_e^0$ (mag arcsec $^{-2}$) (10)	σ_{e8} (km s $^{-1}$) (11)	
IC 3957	6350	1.00	3.73	3.73	18.48	0.01	0.02	0.10	18.34	157
IC 4041	7114	1.00	12.59	12.59	20.14	0.01	0.02	0.11	19.99	117
NGC 4798.....	7838	0.76	46.96	41.27	21.20	0.01	0.02	0.13	21.34	163
NGC 4807.....	6941	0.81	6.80	6.16	18.34	0.01	0.02	0.11	18.42	236
NGC 4821.....	6974	0.62	11.69	9.43	19.44	0.01	0.02	0.11	19.82	173
NGC 4827.....	7650	0.87	12.45	11.65	19.18	0.01	0.02	0.12	19.18	293
NGC 4839.....	7346	0.49	33.07	24.57	20.23	0.01	0.02	0.12	20.85	241
NGC 4842.....	7297	1.00	4.87	4.87	18.10	0.01	0.02	0.12	17.95	212
NGC 4849.....	5885	0.78	13.04	11.58	19.12	0.01	0.02	0.09	19.26	218
NGC 4859.....	7055	0.63	12.43	10.12	19.49	0.01	0.02	0.11	19.84	221
NGC 4874.....	7175	1.00	52.91	52.91	20.86	0.01	0.02	0.11	20.71	195
NGC 4886.....	6345	1.00	9.21	9.21	19.59	0.01	0.02	0.10	19.46	151
NGC 4889.....	6497	0.65	35.74	29.37	19.61	0.01	0.02	0.10	19.95	392
NGC 4919.....	7110	0.62	9.34	7.54	18.97	0.01	0.02	0.11	19.35	169
NGC 4931.....	5849	0.39	11.32	7.84	18.46	0.01	0.02	0.09	19.36	211
NGC 4944.....	7111	0.34	33.49	22.36	19.92	0.01	0.01	0.11	20.95	196
NGC 4952.....	5919	0.62	12.78	10.31	18.81	0.01	0.02	0.09	19.20	232
Maffei 1 ^a	66.4	0.73	203.60	150.17	21.25	1.69	2.65	0.00	19.01	180.0
Maffei 1 uncertainties	5.0	0.01	10.00	7.38	0.04	0.07	0.11	...	0.11	7.4

NOTE.—Col. (1): Name of galaxy. Col. (2): Heliocentric radial velocity from SGHb. Col. (3): Ratio of the semiminor to the semimajor axis, computed from $\log R_{25}$ from RC3. Col. (4): Effective radius in I , corrected for seeing effects, from the $r^{1/4}$ fit to the surface brightness profile. Col. (5): Effective aperture radius, computed from r_e following Olson & de Vaucouleurs 1981. Col. (6): Measured mean effective I -band surface brightness, defined by SGHa as $\langle \mu \rangle_e = \mu(r_e) - 1.392$. Col. (7): Optical depth at 1 μm due to dust, derived from redshifts of Schlegel, Finkbeiner, & Davis 1998 following McCall 2003. Col. (8): I -band Galactic extinction, computed from τ_1 following McCall 2003. Col. (9): I -band correction for K -effect, according to McCall 2003, plus $2.5 \log(1+z)^4$ correction for surface brightness dimming. Col. (10): Mean effective face-on I -band surface brightness corrected for seeing, Galactic extinction, and cosmological effects (i.e., $\langle \mu \rangle_e^0 = \langle \mu \rangle_e - A_I^{\text{sec}} - A_I^{\text{gal}} - A_I^c - 2.5 \log b/a$, where $A_I^{\text{sec}} = 0.016 \text{ mag arcsec}^{-2}$ following SGHa). Col. (11): Velocity dispersion corrected for aperture effect using eq. (2) of Jørgensen, Franx, & Kjærgaard 1995 with $\theta_{\text{obs}} = 2''$ (SGHb).

^a For Maffei 1, the values in cols. (3)–(6) are taken from the photometry of Buta & McCall 1999. Cols. (2), (7), and (11) contain the measurements determined in this study, with the velocity dispersion corrected for aperture effect using eq. (2). Note that col. (10) for Maffei 1 does not include a correction for seeing.

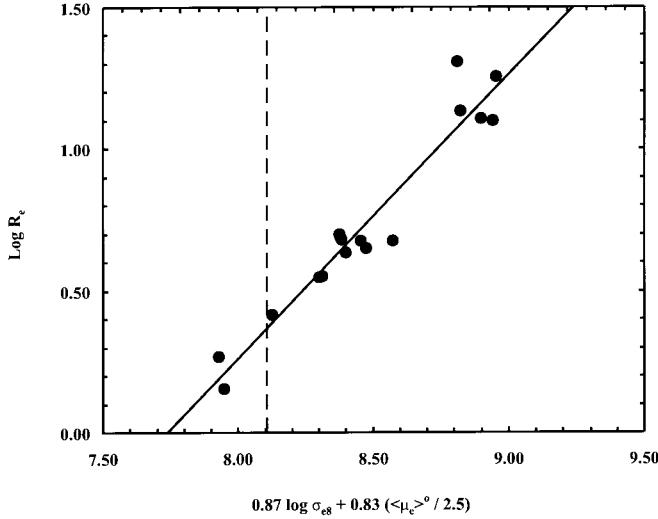


FIG. 4.—*I*-band FP. The solid line marks the linear least-squares fit. The rms scatter in $\log R_e$ is 0.09. The dashed line marks the location of Maffei 1.

data without the axis ratio correction yields $\alpha = 1.18 \pm 0.24$ and $\beta = 0.90 \pm 0.08$. These values are consistent within errors with the results of Jørgensen et al. (1996), who, from photometry in Gunn *r*, found $\alpha = 1.24 \pm 0.07$ and $\beta = 0.82 \pm 0.02$.

The FP parameters for Maffei 1 are given at the bottom of Table 2. The effective radius r_e and effective surface brightness $\mu(r_e)$ were measured by Buta & McCall (1999) via a free-ellipse fit to the *I*-band surface brightness profile, exactly as was done for the elliptical galaxies used to construct the FP. The surface brightness was corrected for inclination using the mean axis ratio of the outer isophotes in *I* (Buta & McCall 1999). This quantity was used in place of $\log R_{25}$ to avoid the uncertainty introduced by the heavy extinction in the *B* band. Based on equation (6), $\log R_e = 0.460 \pm 0.051$ for Maffei 1. Thus, the FP distance to Maffei 1 is 2.92 ± 0.37 Mpc. The error comes from the uncertainty in the fit and the errors in the measurements of r_e , μ_e , and σ for Maffei 1. The uncertainty in the distance to the Coma Cluster is not included.

Since there is now wide-field surface photometry available in *B* (Buta & McCall 1999), it is possible to determine the distance to Maffei 1 with some confidence from the D_n - σ relation, too (Lynden-Bell et al. 1988). It is of benefit to do so because the photometry involved and the calibration of the relation are completely independent of those employed in our FP analysis in *I*. The technique relates the Hubble velocity v_H to the velocity dispersion σ and the diameter D_n within which the mean *B*-band surface brightness is 20.75 mag arcsec⁻². From Lynden-Bell et al. (1988),

$$\log v_H = 1.2 \log \sigma - \log D_n + 1.411, \quad (7)$$

where v_H is in units of km s⁻¹, σ is in units of km s⁻¹, and D_n is in units of 0'1. For σ , we have 176 ± 7 km s⁻¹, which is the velocity dispersion measured in § 4.2 after the aperture correction of Davies et al. (1993), instead of that of Jørgensen et al. (1995), for consistency with the definition of this parameter by Lynden-Bell et al. (1988). We note that this value is 24 km s⁻¹ less than the value of 200 ± 50 km s⁻¹ adopted by Luppino & Tonry (1993) in their D_n - σ analysis. For the *B*-band extinction, we use $A_B = 6.12 \pm 0.25$ mag,

derived from the value of τ_1 obtained here using $R_B^1 = A_B/\tau_1 = 3.623$. The surface photometry of Buta & McCall (1999) gives $D_n = 366'' \pm 77''$. Application of equation (7) yields $v_H = 209 \pm 58$ km s⁻¹, which we increase by 17% to compensate for “Malmquist bias” according to the prescription of Lynden-Bell et al. (1988; their eq. [2.11]). The Hubble constant is 79.2 ± 9.9 km s⁻¹ Mpc⁻¹, based on the Cepheid calibration of Freedman et al. (2001), reanchored to the maser distance of NGC 4258 (see Newman et al. 2001). Thus, the corrected velocity corresponds to a distance of 3.08 ± 0.85 Mpc, where once again the uncertainty in the zero point of the distance scale has been excluded. The large error bar is predominantly due to the uncertainty in the *B*-band photometry and extinction.

A value of D_n can be estimated as well from the K' photometry of Luppino & Tonry (1993), but using an actual measurement of $B-K'$ now. The effective *B* magnitude is given by Buta & McCall (1999), and the effective K' magnitude within the effective aperture defined for *B* (Buta & McCall 1999) can be measured from the aperture growth curve of Luppino & Tonry (1993). The resulting $B-K'$ color is 3.85 ± 0.27 mag, versus 4.2 mag adopted by Luppino & Tonry (1993). From the K' surface brightness profile of Luppino & Tonry (1993), we measure $D_n = 375'' \pm 41''$ using the revised color. Performing the same analysis as above, we obtain a D_n - σ distance of 3.23 ± 0.67 Mpc.

Although distances determined from the brightest stars in K' are suspect, we have no grounds to reject the new values from the D_n - σ relation. Consequently, the distance we adopt for Maffei 1 is 3.01 ± 0.30 Mpc, which is the weighted average of the result from the FP and the mean of the two estimates from the D_n - σ relation. The error does not include that in the zero point of the distance scale. It also does not include the uncertainty in the shape of the reddening law, but this is thought to be small in comparison to the error in the measurement of the extinction (see McCall & Armour 2000 and Buta & McCall 2003).

7. DISCUSSION

To properly compare our result with the distance estimates of Luppino & Tonry (1993) and Davidge & van den Bergh (2001) derived from the brightest stars in K' , we revise their results using the Galactic extinction of Maffei 1 found in this study and our adopted distance scale anchored to the maser distance of NGC 4258. The result of Luppino & Tonry (1993) moves in from 4.2 ± 1.1 to 4.0 Mpc, and the result of Davidge & van den Bergh (2001) comes in from $4.4^{+0.6}_{-0.5}$ to 4.2 Mpc. Our new distance is significantly closer.

As stated in § 1, both of the K' analyses required the adoption of an intrinsic luminosity for the brightest giants in K' , which was judged from observations of M32 and the bulge of M31. Luminosities of stars at the tip of the AGB are very sensitive to age (Bressan et al. 1994); over 2–14 Gyr, $M_{K'}$ becomes fainter by roughly 1 mag. M32 is known to host a population of luminous AGB stars, evidence of an episode of star formation in the last 2 Gyr (Freedman 1992; Bressan et al. 1994). The bulge of M31 may be similarly affected, given that the very brightest stars at K' have absolute magnitudes close to those in M32 (Davidge 2001). In Maffei 1, the lack of an unusually large color gradient (Buta & McCall 1999) and the negligible H α emission (Buta & McCall 2003) suggest that star formation has not occurred recently. Consequently, it may be postulated that AGB stars in Maffei 1

are more likely to lie on the opposite end of the age scale from their counterparts in M31 and M32. If the age of the brightest AGB stars in Maffei 1 were around 10 Gyr, whereas the age of such stars in M32 and in the bulge of M31 were more like 2–4 Gyr, absolute K' magnitudes would be fainter in Maffei 1 by roughly 0.5 mag. With the bulge of M31 as the reference field, the distance of Davidge & van den Bergh (2001) would be lowered to 3.4 Mpc, and the Luppino & Tonry (1993) distance would be reduced to 3.0 Mpc. Both of these values are in line with our measurement.

The role that the three dominant members of the IC 342/Maffei group have played in the evolution of the Milky Way and its neighbors has been a subject of controversy because of their uncertain distances. Previous estimates of the radial velocities and distances to Maffei 1 and IC 342 suggested that these galaxies could have been in the vicinity of the Local Group within the last 5–8 Gyr (McCall 1989; Valtonen et al. 1993), in the process affecting its early dynamical evolution. This conclusion is all the more significant given that a fundamental tenet of Local Group timing is that the Milky Way and M31 have always behaved dynamically like an isolated pair.

The new velocity and distance for Maffei 1 make possible a new judgment about the galaxy's relevance to the Local Group. With a heliocentric velocity of 66.4 km s^{-1} , the velocity of Maffei 1 with respect to the centroid of the Local Group is 311 km s^{-1} (Courteau & van den Bergh 1999). Adopting $H_0 = 79.2 \text{ km s}^{-1} \text{ Mpc}^{-1}$, the Hubble distance to Maffei 1 is 3.9 Mpc. This is somewhat higher than the distance computed above, but it is easily possible that it is distorted by the peculiar motion of Maffei 1 arising from its association with the IC 342/Maffei Group. The mean velocity of the three dominant galaxies relative to the Local Group is 264 km s^{-1} , where the recessional velocities of Maffei 2 and IC 342 have been adopted to be those given by Hurt, Turner, & Ho (1996) and Newton (1980), respectively. At this velocity, the Hubble distance comes down to 3.3 Mpc, which is consistent with our result. We therefore conclude that it is unlikely that Maffei 1 has interacted with the Local Group since the big bang. Further discussion of this issue will be given in a later paper, where modern distances to IC 342 and Maffei 2 will be derived and shown to be close to that derived here for Maffei 1.

8. SUMMARY

New spectroscopy of Maffei 1 at low and high resolution has been presented. The Mg_2 index has been measured for the first time, and the heliocentric velocity and velocity dispersion have been derived with improved accuracy.

The Mg_2 index was used to reevaluate the extinction. To avoid the uncertainties inherent in B -band photometry of Maffei 1, the relationship between Mg_2 and $V-I$ for elliptical galaxies was examined by constructing a sample of relatively unobscured objects with existing photometry. A strong correlation was discovered, which was employed to estimate the intrinsic $V-I$ color and, thus, $E(V-I)$ for Maffei 1. Taking care to compensate for the effect of extinction on the Mg_2 index and on shifts in effective wavelengths, the optical depth at $1 \mu\text{m}$ due to Galactic dust was estimated to be $\tau_1 = 1.69 \pm 0.07$. Integrating an appropriately extinguished SED for an elliptical galaxy through the response curve for the V filter, $A_V = 4.67 \pm 0.19$ mag. The value of $A_V = 5.1 \pm 0.2$ mag found by Buta & McCall (1983) was an

overestimate because of inadequate or incorrect compensation for effective wavelength shifts.

The distance of Maffei 1 was derived by constructing the FP for the Coma Cluster in I , then taking the weighted average of the FP distance and the mean of two estimates from the $D_n-\sigma$ relation. The result is 3.01 ± 0.30 Mpc. It is lower than the estimates of Luppino & Tonry (1993) and Davidge & van den Bergh (2001), which are founded on the brightest stars seen at K' . We suggest that this discrepancy is due to their assumption of similar stellar populations among Maffei 1, M31, and M32, despite indications to the contrary.

The revised properties of Maffei 1 are summarized in Table 3. The apparent magnitude in V after correction for

TABLE 3
PROPERTIES OF MAFFEI 1

Property	Value
Apparent total magnitudes:	
B_T^a	13.47 ± 0.09 mag
V_T^a	11.14 ± 0.06 mag
I_T^a	8.06 ± 0.04 mag
Apparent total colors:	
$(B-V)_T^a$	2.33 ± 0.12 mag
$(V-I)_T^a$	3.08 ± 0.07 mag
Heliocentric radial velocity v_\odot	$66.4 \pm 5.0 \text{ km s}^{-1}$
Velocity dispersion σ	$186.8 \pm 7.4 \text{ km s}^{-1}$
Mg_2 index within $\theta_e/8$	0.238 ± 0.061 mag
Intrinsic effective $V-I$ color $(V-I)_e^0$	1.100 ± 0.065 mag
$V-I$ color excess $E(V-I)$	2.020 ± 0.082 mag
Optical depth at $1 \mu\text{m}$ due to dust τ_1	1.688 ± 0.068
Extinction normalized to τ_1 :	
R_B^1	3.623
R_V^1	2.765
R_I^1	1.569
R_K^1	0.336
Galactic extinction:	
A_B	6.12 ± 0.25 mag
A_V	4.67 ± 0.19 mag
A_I	2.65 ± 0.11 mag
A_K	0.57 ± 0.02 mag
Apparent total magnitudes corrected for Galactic extinction:	
$B_T^0{}^b$	7.35 ± 0.26 mag
$V_T^0{}^b$	6.47 ± 0.20 mag
$I_T^0{}^b$	5.41 ± 0.11 mag
Apparent total color $(B-V)_T^0$ corrected for Galactic extinction ^b	
	0.88 ± 0.13 mag
Apparent total color $(V-I)_T^0$ corrected for Galactic extinction ^b	
	1.06 ± 0.09 mag
Semimajor axis of the elliptical isophote at $\mu_B^0 = 25 \text{ mag arcsec}^{-2}$, corrected for Galactic extinction (D_{25}^0)	
	23.4 ± 1.2
Distance D^c	3.01 ± 0.30 Mpc
Distance modulus μ	27.39 ± 0.22
Absolute magnitudes:	
M_B	-20.04 ± 0.34 mag
M_V	-20.92 ± 0.30 mag
M_I	-21.98 ± 0.25 mag

^a Values from Buta & McCall 1999.

^b Cosmological corrections at this redshift are negligible.

^c Based on a distance to Coma of 78.8 Mpc, which is the average value measured from the FP in Gunn r and from the Tully-Fisher relation in I (see Freedman et al. 2001), but anchored to the maser distance of NGC 4258 (7.2 Mpc; see Herrnstein et al. 1999) rather than to the Cepheid distance of the LMC (0.05 Mpc; see Freedman et al. 2001).

extinction shows that Maffei 1 is among the brightest galaxies in the northern sky. Knowing the extinction, the apparent $B-I$ color and the surface brightness profile in I can be used to judge the unextinguished diameter at the standard isophote (i.e., 25 mag arcsec $^{-2}$ in B). Based on the fixed-ellipse profile of Buta & McCall (1999), the diameter of Maffei 1 is 23.4 ± 1.2 , which is $\frac{2}{3}$ that of the full Moon.

The only other nearby galaxy in the class of Maffei 1 is Centaurus A. Marleau et al. (2000) give a detailed summary of distance estimates to this galaxy and adopt the weighted mean. We modify their result by shifting the distance to the NGC 4258 zero point adopted throughout this paper (Freedman et al. 2001; Newman et al. 2001). We also update the estimate obtained from surface brightness fluctuations (SBFs) in I (Israel 1998), which are known to be a more robust distance indicator than fluctuations in K' . Tonry et al. (2001) present a new I -band calibration, which we apply to the fluctuation magnitude measured by Tonry & Schechter (1990). The resulting distance modulus is 28.05 ± 0.11 mag, corrected to the NGC 4258 zero point. In the derivation of this value, the extinction corrections

employed were obtained from $E(B-V)$ (Schlegel et al. 1998) in the manner described for Maffei 1. After substituting this result for the previous SBF distance adopted by Marleau et al. (2000), we obtain a weighted mean distance modulus of 27.77 ± 0.07 mag, which corresponds to 3.6 ± 0.1 Mpc. The distance estimates to Maffei 1 from the FP and $D_n-\sigma$ relation suggest that Maffei 1 is closer, making it the nearest giant elliptical galaxy to the Milky Way. However, based on the total apparent magnitude given in the Lyon Extragalactic Database ($V_T = 6.72$), the absolute magnitude of Cen A is $M_V = -21.71$ mag. Maffei 1 is fainter by 0.8 mag.

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