The Galactic Extinction towards Maffei 1

R. Buta – The University of Texas at Austin
M. McCall – The University of Texas at Austin

Deposited 08/01/2019

Citation of published version:


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Ronald J. Buta and Marshall L. McCall

Department of Astronomy and McDonald Observatory, The University of Texas at Austin, and Mount Stromlo and Siding Spring Observatories, Research School of Physical Sciences, The Australian National University

Received 1983 January 19; in original form 1982 August 23

Summary. The extinction of Maffei 1 has been measured by two new techniques. First, \( BV \) aperture photometry has been performed to obtain the colour excess from standard aperture—colour relations for early-type galaxies. Secondly, millimetre and radio observations of galactic CO and \( \text{HI} \) have been used to calculate the total hydrogen column density along the line-of-sight, and thereby estimate the colour excess from the local dust-to-gas ratio. After consideration of all extinction measurements to date, it is concluded that \( A_V = 5.1 \pm 0.2 \) mag. The isophotal diameter and the corrected apparent visual magnitude are estimated to be \( \sim 15 \) arcmin and \( \sim 6.3 \) respectively (assuming type E), making Maffei 1 one of the biggest and brightest galaxies in the sky. The distance is found to be \( 2.1^{+0.3}_{-0.8} \text{ Mpc} \), indicating that Maffei 1 is probably associated with the Ursa Major—Camelopardalis cloud, not the Local Group. The primary source of error in the distance is now the uncertainty in the central velocity dispersion.

1 Introduction

The status of the heavily obscured galaxy Maffei 1 (A 0232 + 59) with respect to the Local Group is still uncertain. On the basis of a coordinated program of spectroscopy and infrared photometry, Spinrad \textit{et al.} (1971) identified Maffei 1 as a giant elliptical galaxy and suggested that it is an unbound member of the Local Group. However, inconsistencies in the derived value of the foreground galactic extinction have made this interpretation questionable. Spinrad \textit{et al.} (1971) derived a visual absorption \( A_V = 5.2 \pm 0.2 \text{ mag} \) from a comparison of the integrated nuclear spectrum of Maffei 1 with that of typical giant ellipticals and early spirals. However, Kohoutek & Haug (1972) obtained only \( A_V = 3.1 \pm 0.4 \text{ mag} \) from star counts and application of the \( Q \)-method to early-type stars in the field. The difference between the values is significant, and the lower value, if correct, would imply that Maffei 1 is not a member of the Local Group. A later study by Nandy & Smriglio (1973) on the distribution of M stars towards Maffei 1 and of OB stars towards the \( \text{HII} \) region IC 1805 (due
north of the galaxy) has given some support to the higher value of $A_V$. Nevertheless, each method involves uncertainties, and independent determinations are needed in order to definitively resolve the discrepancy.

In this paper, we present two new determinations of the extinction towards Maffei 1. First, the total (or asymptotic) colour index $(B-V)_T$ of the galaxy is measured and compared with the mean intrinsic colour index $(B-V)_W$ of galaxies of similar Hubble type. Secondly, the total column density of galactic hydrogen towards Maffei 1 is derived from observations of $^{12}$CO and $^{13}$CO and published H I data, in order to determine the colour excess from the local dust-to-gas ratio. The first method is similar in principle to that used by Spinrad et al. (1971). The second measures the total extinction due to the galactic disc alone, and is independent of assumptions about the intrinsic properties of Maffei 1.

The morphological classification of Maffei 1 is reviewed in Section 2. The photometric analysis is presented in Section 3 and the CO–H I analysis in Section 4. In Section 5, seven galactic extinction estimates thus far obtained are summarized, and a final value of $A_V$ is decided upon. This is then combined with the apparent magnitude determined from multi-aperture photometry and the absolute magnitude indicated by the central velocity dispersion to derive the distance.

2 The Hubble type of Maffei 1

The exact Hubble type of Maffei 1 is uncertain due to the heavy obscuration. A deep IIIa-J photograph presented by Spinrad et al. (1971) suggests that Maffei 1 is an elliptical galaxy, perhaps of type E3 or E4. Additional support for such an early classification can be found from direct comparison of the appearance of Maffei 1 with that of its neighbour Maffei 2, which is only 42 arcmin to the east. Despite the high galactic absorption, Maffei 2 is obviously a spiral, as indicated from deep photographs obtained by Spinrad et al. (1973), who adopted a classification of Sbc.

Ford & Jenner (1971) reported that a distinct arc of absorption can be seen less than 1 arcmin from the centre of Maffei 1. The small scale of the feature suggests that it probably is associated with Maffei 1 (van den Bergh 1971a). If so, the galaxy must be later than E, perhaps S0. However, since it cannot be completely ruled out that the arc is instead superimposed galactic material, we will derive the photometric parameters of Maffei 1 on the assumption that its Hubble type is between a true elliptical and a late lenticular, or $-5 < T < -1$ (see de Vaucouleurs, de Vaucouleurs & Corwin 1976, hereafter designated RC2).

3 Photometric analysis

3.1 OBSERVATIONS

Photometric observations of Maffei 1 were obtained on nine nights between 1978 October and 1980 October with a 1P21 photoelectric photometer attached to the 0.91- and 2.1-m telescopes of McDonald Observatory. The same set of standard $UBV$ filters ($U = 1$ mm Schott UG2, $B = 2$ mm Corning 5030 + 2 mm Schott GG13 and $V = 2$ mm Corning 3384) was used on each night. The red leak of the $U$ filter was blocked by 3 mm of CuSO$_4$. Transformations to the $UBV$ system were made from nightly observations of 10–14 Landolt (1973) standards, including several pairs of extinction stars. The final reduction to the standard $UBV$ system was based on the mean extinction and transformation coefficients for each separate observing run. These means were typically 0.14, 0.08 and 0.27 for the first order $V$, $(B-V)$ and $(U-B)$ extinction coefficients and $-0.03$, 1.02 and 0.98 for the corresponding transformation slopes.
Plate 1. Field chart of Maffei 1. The large photograph is taken from the E print of the Palomar Sky Survey. The ellipse indicates the approximate 25.0 mag arcsec$^{-2}$ (corrected $B$) isophote. The inset shows a close-up of Maffei 1 from the O print. The stars measured to correct the aperture photometry are marked. (Copyright by the National Geographic Society–Palomar Observatory Sky Survey. Reproduced by permission from the California Institute of Technology.)
Table 1. Photometry of Maffei 1.

<table>
<thead>
<tr>
<th>A (arcsec)</th>
<th>log A</th>
<th>V</th>
<th>B-V</th>
<th>V</th>
<th>B-V</th>
<th>Date</th>
<th>Telescope (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>14.6</td>
<td>0.39</td>
<td>15.09</td>
<td>2.46</td>
<td>80 Oct 05</td>
<td>2.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.39</td>
<td>15.14</td>
<td>2.39</td>
<td>80 Oct 06</td>
<td>2.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>29.4</td>
<td>0.69</td>
<td>14.30</td>
<td>2.39</td>
<td>80 Oct 05</td>
<td>2.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>32.5</td>
<td>0.70</td>
<td>14.30</td>
<td>2.45</td>
<td>80 Feb 10</td>
<td>2.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.73</td>
<td>14.12</td>
<td>2.34</td>
<td>79 Dec 20</td>
<td>0.91</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.73</td>
<td>14.09</td>
<td>2.44</td>
<td>79 Dec 22</td>
<td>0.91</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.73</td>
<td>14.13</td>
<td>2.38</td>
<td>79 Dec 25</td>
<td>0.91</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>65.4</td>
<td>1.04</td>
<td>11.75</td>
<td>1.46</td>
<td>78 Oct 29</td>
<td>0.91</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.009</td>
<td>0.008</td>
<td>0.011</td>
<td></td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>1.04</td>
<td>11.74</td>
<td>1.49</td>
<td>79 Dec 18</td>
<td>0.91</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.04</td>
<td>11.75</td>
<td>1.48</td>
<td>79 Dec 20</td>
<td>0.91</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.04</td>
<td>11.73</td>
<td>1.48</td>
<td>79 Dec 22</td>
<td>0.91</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>131.8</td>
<td>1.34</td>
<td>11.35</td>
<td>1.42</td>
<td>79 Dec 22</td>
<td>0.91</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.34</td>
<td>11.34</td>
<td>1.44</td>
<td>79 Dec 22</td>
<td>0.91</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.34</td>
<td>11.33</td>
<td>1.42</td>
<td>79 Dec 25</td>
<td>0.91</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* A = 65.4 arcsec corrected for stars A, B and F; A = 131.8 arcsec corrected for stars A–F.

To define the magnitude–aperture and colour–aperture relations, observations were made with five different field apertures. The diameters ranged from 15 arcsec to 2.2 arcmin. Table 1 summarizes the data obtained in B and V only. (U–B) colours are not tabulated, because the scatter in the measurements was very large, possibly due to residual light from field stars.

There were three principal difficulties which were encountered in the photometry. First, observations with the two largest apertures (A = 65.4 and 131.8 arcsec) were affected by field stars. Since the largest apertures are most important for the total magnitude, we measured as many of the stars as possible to correct for their contribution. The stars measured are identified in Plate 1 and listed in Table 2. In each case, sky readings were taken close to the star parallel to the isophotes of the galaxy (approximately east–west) as seen on photographs. Stars A–E were the most significant contributors to the light measured with the 131.8 arcsec aperture, accounting for 82 per cent of the flux in B and 70 per cent of the flux in V. In the 65.4 arcsec aperture, stars A, B and F contributed 86 per cent of the light in B and 76 per cent of the light in V.

Table 2. Photometry of field stars surrounding Maffei 1.

<table>
<thead>
<tr>
<th>Star</th>
<th>V</th>
<th>B–V</th>
<th>U–B</th>
<th>N</th>
<th>V</th>
<th>B–V</th>
<th>U–B</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>12.23</td>
<td>1.32</td>
<td>1.26</td>
<td>5</td>
<td>0.009</td>
<td>0.008</td>
<td>0.011</td>
</tr>
<tr>
<td>B</td>
<td>14.00</td>
<td>1.34</td>
<td>1.24</td>
<td>3</td>
<td>0.015</td>
<td>0.021</td>
<td>0.042</td>
</tr>
<tr>
<td>C</td>
<td>13.56</td>
<td>1.01</td>
<td>0.70</td>
<td>4</td>
<td>0.012</td>
<td>0.009</td>
<td>0.014</td>
</tr>
<tr>
<td>D</td>
<td>15.38</td>
<td>1.20</td>
<td>0.48</td>
<td>3</td>
<td>0.023</td>
<td>0.023</td>
<td>0.009</td>
</tr>
<tr>
<td>E</td>
<td>15.64</td>
<td>0.87</td>
<td>0.43</td>
<td>3</td>
<td>0.003</td>
<td>0.028</td>
<td>0.067</td>
</tr>
<tr>
<td>F</td>
<td>16.84</td>
<td>1.60</td>
<td>1.76</td>
<td>1</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>G</td>
<td>12.22</td>
<td>1.50</td>
<td>1.13</td>
<td>2</td>
<td>0.015</td>
<td>0.000</td>
<td>0.055</td>
</tr>
</tbody>
</table>
In view of the seriousness of the contamination, the accuracy of the star subtraction depends critically on the uniformity of the response of the photometer across the apertures and the effects of light scattering and seeing. Stellar drift scans were made at the beginning of each observing run in order to accurately align the photocathode with the Fabry lens. In this way, it was possible to obtain a cathode response flat to 1 per cent or better. The effects of light scattering and seeing were tested by measuring the net flux from a star with the 65.4, 32.5 and 16.0 arcsec apertures. Due mainly to scattering by dust on the primary mirror, it was found necessary to apply a correction of +0.02 mag to the photometry made with apertures 32.5 arcsec and larger. The corrected Maffei 1 measurements, both before and after the field star subtraction, are given in Table 1.

The second difficulty concerns the extreme redness of Maffei 1. Only two stars in the Landolt catalogue, 110 - 353 and 110 - 502, were found to be nearly red enough to match the colour of the galaxy. The former star seems to be an excellent red standard, with \( (B-V) = 1.98 \pm 0.011 \), while the latter, though very well observed by Landolt, has \( (B-V) = 2.27 \pm 0.066 \). We did not find significant departures of these stars from the transformation lines defined by bluer stars, and hence we believe that the small extrapolation required for Maffei 1 has not led to a serious error.

The third problem was that the richness of the star field surrounding Maffei 1 limited the choice of sky fields available for correction, especially for the larger apertures. In most of the observations, sky readings were taken in a field about 5.5 arcmin east of Maffei 1 which appeared devoid of stars visually and which included only a few very faint stars visible on the E print of the Palomar Sky Survey. These stars actually might help to compensate for the faintest stars in the local field of Maffei 1, which could not be measured. According to Spinrad et al. (1971), Maffei 1 can be traced to at least 3 arcmin radius in the infrared, which means that the sky field may have included the outer parts of the galaxy. To determine how significant the contribution could be, we computed the mean surface brightness of Maffei 1 in three nearly concentric rings defined by the aperture photometry. As will be shown below, the resulting profile is represented well by a de Vaucouleurs' \( r^{1/4} \) law which, if extrapolated to \( r = 5.5 \) arcmin, indicates that Maffei 1 could have contributed approximately 1 per cent of the night sky flux at this radius. This could lead to systematic errors of a few per cent in our photometry, depending on the aperture diameter. However, we believe these errors to be insignificant compared to the statistical errors in the photometry and in the star subtraction, and, therefore, no correction for the effect will be made.

### 3.2 Integrated Magnitude, Colour Index and Diameter from Aperture Photometry

Fig. 1(a) shows the \((V, \log A)\) aperture—magnitude relation ('growth-curve') for Maffei 1 while Fig. 1(b) shows the \((B-V, \log A)\) relation. We consider the magnitude—aperture relation in \( V \) light rather than the usual \( B \) light, partly because \( V \) is more precisely determined for this galaxy, but mostly because the colour—aperture curve indicates a serious problem with the \( B \) magnitudes derived from the larger apertures. Fig. 1(b) shows that Maffei 1 is of a nearly uniform colour within an aperture of 32.5 arcsec, but becomes bluer by 0.3 mag between the 32.5 and 131.8 arcsec apertures. Such a steep radial colour gradient is extremely abnormal for a galaxy in the range \(-5 < T < -1\), where the asymptotic colour differences \( \delta (B-V) = (B-V)_{\text{nuc}} - (B-V)_{T} \) are generally less than 0.06 mag (see the standard colour—aperture relations illustrated in RC2). The colour index measurements of Maffei 1 in the larger apertures are therefore probably affected by a large systematic error, the cause of which must be either inaccurate or incomplete subtraction of the light of...
Figure 1. Aperture photometry of Maffei 1. (a) $V$ versus log $A$. The solid curve is the best fit of the standard magnitude–aperture relation for elliptical galaxies. (b) $B-V$ versus log $A$. The solid curve is the fit of the standard colour–aperture relation for ellipticals. Points in brackets are uncertain and may be in systematic error (see text).

the field stars. The $V$ flux due to stars included in the large apertures but not measured and subtracted probably amounts to less than 10 per cent of the flux due to Maffei 1. However, these stars must be, on average, considerably bluer than the galaxy (note that $<B-V> = 1.26 \pm 0.10$ for the seven stars in Table 2), so they may substantially disturb the large aperture $B$ magnitude measurements.

We decided that the total $(B-V)$ colour of Maffei 1 should be derived only from the measurements with the two smaller apertures. On the assumption that the smaller apertures are essentially measuring the nuclear colour, the mean colour for these apertures $<B-V> = 2.41 \pm 0.02$ suggests that the integrated colour of the galaxy is in the range $2.38 \leq (B-V)_T \leq 2.35$ ($-5 < T < -1$), according to the asymptotic colour differences illustrated in fig. 6 of RC2. Thus, the derived integrated colour is quite insensitive to Hubble type if Maffei 1 is earlier than $S0^*$, provided that the intrinsic colour gradient is not grossly abnormal. The dispersion in colour gradients at a given $T$ will be reflected partly by the dispersion in $(B-V)_T^0$, which will be introduced into the error analysis below.

In principle, the total magnitude $V_T$ of Maffei 1 could be estimated by fitting standard growth curves to the magnitude–aperture data. However, this method is uncertain for
Table 3. Photometric parameters.

<table>
<thead>
<tr>
<th>Assumed</th>
<th>Maffei 1</th>
<th>RC2 Galaxies</th>
<th>Hubble Stage</th>
<th>( D_0/Ae )</th>
<th>([m'_e(V)]_0)</th>
<th>( V_T )</th>
<th>( D_0 )</th>
<th>([m'_e(V)]_0)</th>
<th>( R(m'_e)_0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>(2)</td>
<td>(3)</td>
<td>(4)</td>
<td>(5)</td>
<td>(6)</td>
<td>(7)</td>
<td>(8)</td>
<td>(9)</td>
<td>(10)</td>
</tr>
<tr>
<td>-5</td>
<td>0.03</td>
<td>0.894</td>
<td>0.494</td>
<td>20.14</td>
<td>11.39</td>
<td>2.38</td>
<td>1.67</td>
<td>1416</td>
<td>19.02</td>
</tr>
<tr>
<td>-3</td>
<td>0.04</td>
<td>0.863</td>
<td>0.075</td>
<td>20.39</td>
<td>11.87</td>
<td>2.37</td>
<td>1.39</td>
<td>1416</td>
<td>19.02</td>
</tr>
<tr>
<td>-2</td>
<td>0.05</td>
<td>0.856</td>
<td>0.354</td>
<td>20.14</td>
<td>12.00</td>
<td>2.36</td>
<td>1.32</td>
<td>1416</td>
<td>19.02</td>
</tr>
<tr>
<td>-1</td>
<td>0.06</td>
<td>0.808</td>
<td>0.101</td>
<td>20.05</td>
<td>12.16</td>
<td>2.35</td>
<td>1.24</td>
<td>1416</td>
<td>19.02</td>
</tr>
</tbody>
</table>

Explanations: Col. (1) Stage on RC2 numerical scale; (2) mean asymptotic colour difference between nuclear region and total colour index, from standard colour-aperture relations; (3) mean and standard deviation of fully corrected colours from de Vaucouleurs (1977); (4) mean and standard deviation of logarithmic (blue light) diameter ratio, where \( D_0 \) is the fully corrected isophotal diameter at \( \mu_B = 25.0 \) mag sec\(^{-2}\) and \( Ae \) is the effective aperture transmitting half the blue light flux; (5) mean and standard deviation of extinction corrected mean effective surface brightness (within \( Ae \)) in mag sec\(^{-2}\); (6) total magnitude \( V_T \) estimated from graphical fits of aperture photometry to mean \( V \) magnitude-aperture curves, and \( V_T^O = V_T - 5.1 \); (7) integrated colour index \( (B-V)_T = 2.41 - \delta (B-V) \); and \( E(B-V) = (B-V)_T - (B-V)_T^O \); (8) effective aperture \( Ae(V) \) in visual light estimated from graphical fits to mean \( V \) magnitude-aperture curves, and predicted isophotal diameter in blue light \( D_0 \) using values in col. 4 and assuming \( Ae(B) = Ae(V) \); (9) mean effective surface brightness in visual light, before and after correction for extinction; (10) mean surface brightness residual of Maffei 1 in units of standard deviation (col. 5): \( R(m'_e)_0 = [m'_e(V)]_0 - [m'_e(V)]_0 \).

Maffei 1 because the aperture sizes are sufficiently small relative to the true size of the galaxy that \( V \) varies nearly linearly with log \( A \). The slope of the relation is confirmed by independent infrared photometry (Spinrad et al. 1971). In Table 3, the results of eye fits for the \( V \) data are collected. Here \( V_T \) was determined by fitting a standard \( V \) curve derived by combining the blue light magnitude-aperture curves with the \( (B-V) \) colour-aperture curves illustrated in figs 5 and 6 of RC2. Table 3 shows that the uncertainty in the Hubble type of Maffei 1 leads to a large uncertainty in \( V_T \). In particular, the extrapolation from the largest aperture to \( V_T \) requires from 0.5 to 1.3 mag. The effective aperture \( Ae \) was also read from the standard curves, and is seen to depend sensitively on the Hubble type as well.

A consistency check on these values is provided by computing the extinction-corrected mean effective surface brightness in visual light, \( [m'_e(V)]_0 = m'_e(V) - A_V \), i.e. the average visual surface brightness within \( Ae \), and comparing it with the observed mean surface brightness for galaxies of similar Hubble type (also given in Table 3). In every case, Maffei 1 appears to be of abnormally high mean surface brightness (based on \( A_V = 5.1 \) mag, derived below), but it is least unusual if the galaxy is of type E rather than SO. Also, the magnitude-aperture data are best fit by the standard \( V \) curve for an E galaxy, which yields \( V_T = 11.4 \) and \( Ae = 4.7 \) arcmin. This curve is superposed on the data in Fig. 1(a).

The total magnitude and size of Maffei 1 may also be derived by computing the mean surface brightness within the three nearly concentric rings defined by the aperture photometry. As illustrated in Fig. 2, the resulting surface brightness profile appears to obey an
Galactic extinction towards Maffei 1

Figure 2. Average visual surface brightness of Maffei 1 within three nearly concentric rings versus (mean radius)$^{1/4}$. The solid line is a least-squares fit.

$r^{1/4}$ law over the limited range of mean radii (11.5 to 49.3 arcsec). From a least-squares fit we obtain

$$\mu_v(r) = (17.69 \pm 0.07) + (2.198 \pm 0.029) <r>^{1/4} \text{mag arcsec}^{-2}$$

(1)

where $r$ is in arcsec. Here $<r>$ is the average radius of each ring. If equation (1) is extrapolated to infinity, then the standard theoretical relations for the $r^{1/4}$ law (de Vaucouleurs & Pence 1978) yield

$$V_T = 11.05 \pm 0.13 \text{ (int. m.e.)}$$

$$\log D_e = 1.84 \pm 0.05 \text{ (int. m.e.)}$$

where $D_e = 2r_e$ has the units tenths of arcmin. These values are in only fair agreement with those derived from the visual fit to the standard $V$ curve for E galaxies. Since the apertures were not exactly concentrically centred on Maffei 1, and since equation (1) is not based on direct surface photometry (especially important since the isophotes of the galaxy are not circular), the differences are not surprising.

Spinrad et al. (1971) derived $V_T = 11.0$ by assuming a King law for the surface brightness distribution, and measuring the central surface brightness from visual photoelectric photometry and the core radius from infrared photographic surface photometry. This is in good agreement with our estimates if Maffei 1 is an E system, but in poor agreement if Maffei 1 is an S0 system.

Finally, we note that $\log A_e$ can be used as an indirect means of obtaining $D_0$, the fully-corrected face-on isophotal diameter in blue light. This is possible because $\log D_0/A_e$ is nearly independent of type for early-type galaxies ($-5 < T < 0$). An illustration of the sensitivity to type is given by fig. 20 of de Vaucouleurs & Buta (1980). For $-3 < T < -1$, $\log D_0/A_e$ is constant, whereas for $T > 0$ this quantity decreases smoothly with type. From the data for 130 lenticular galaxies in RC2, excluding spindles or any other objects with $\log R_{25} > 0.4$, we computed $\langle \log D_0/A_e \rangle = 0.534 \pm 0.101$ (s.d.). From similar data for 135 elliptical galaxies in the RC2, excluding a number of contact pairs and dwarf systems, we
computed that \( \langle \log D_0/A_e \rangle = 0.494 \pm 0.075 \) (s.d.). Table 3 lists values of \( D_0 \) computed using \( D_0 = 3.12A_e \) for \( T = -5 \) and \( D_0 = 3.42A_e \) for \( -3 < T < -1 \), and assuming \( A_e (B) \sim A_e (V) \) from the magnitude-aperture fits. If Maffei 1 is an E system, then \( D_0 = 14.6 \pm 2.5 \) arcmin, but if it is an SO system, then \( D_0 = 7.1 \pm 2.1 \) arcmin. Note that the latter value is probably excluded, because direct infrared (8000 Å) photographs obtained by Spinrad et al. (1971) with the Palomar 48-in Schmidt telescope indicate that Maffei 1 has a major axis radius of at least 3 arcmin. If the galactic extinction \( A_V \) is 5 mag, then there will still be 3 to 4 mag of extinction at 8000 Å, indicating that Maffei 1 ought to be much larger than 6 arcmin in diameter.

### 3.3 Colour Excess and Galactic Extinction from Colour Observations

The colour excess for Maffei 1 can be estimated from the constraints on \( T \) and the derived value of \( (B-V)_T \). de Vaucouleurs (1977) has compiled a table of fully corrected integrated colours in the \( UBV \) system for galaxies over the whole range of Hubble types \(-5 \leq T \leq 10\). Table 3 summarizes the colours and resulting colour excesses for types \(-5, -3, -2, \) and \(-1\).

Assuming that Maffei 1 has an intrinsic colour which is normal for its type, then \( 1.49 < E (B-V) < 1.54 \). Because the redshift of Maffei 1 is very low \( (V = 15 \) km s\(^{-1}\), given in RC2), the K-correction has a negligible effect on the colour excess. From the measured colour and colour excess, the ratio of total-to-selective extinction is computed to be \( R = 3.5 \pm 0.2 \) (Olson 1975). Thus, for \(-5 < T < -1\),

\[
5.2 < A_V < 5.4 \text{ mag.}
\]

In addition to errors caused by the uncertainty in \( T \), the accuracy of \( A_V \) is subject to the uncertainties in the observations and the assumptions regarding the intrinsic colour and colour gradient. The nuclear colour measurement is believed to be accurate to 0.02 mag. Once emission line objects have been rejected, the standard deviation of the intrinsic colours at a given \( T \) for E and SO galaxies is about 0.05 mag (de Vaucouleurs 1977). The dispersion in the colour gradients (and thus, \( \delta (B-V) \)) at a given \( T \) is not known, but is at least partly reflected by the dispersion in total colours. Combining the uncertainties, we estimate

\[
E (B-V) = 1.51 \pm 0.06.
\]

With the uncertainty in \( R \) included

\[
A_V = 5.3 \pm 0.4.
\]

This result is in excellent agreement with the value of 5.2 mag derived by Spinrad et al. (1971). Less certain K-band photometry by those authors yields, in conjunction with our photometry, \( V-K = 7.55 \), which is also consistent with that of an E/S0 galaxy with extinction of about 5 mag (Frogel et al. 1978).

### 4 HI and CO Analyses

#### 4.1 Background

The correlation between total hydrogen column density and dust column density in the galactic plane can be used to derive the colour excess of an extragalactic object. The advantage of this technique over photometric methods is that no assumptions need be made about the intrinsic properties of the object.

Based on observations of neutral and molecular hydrogen absorption towards early-type stars, Bohlin, Savage & Drake (1978) found that the scatter in the relation between the
column density of H\textsc{i} \([N(\text{H} \textsc{i})]\) and \(E(B-V)\) is in large part due to neglect of \(\text{H}_2\). Significant extinction occurs where hydrogen is predominantly molecular. If the ratio of total-to-selective extinction is computed according to the scheme of Olson (1975) \((R = 3.2\) for each star in the sample), the mean gas-to-extinction ratio for 74 stars (neglecting \(\rho\) Oph), weighted according to colour excess, is

\[
\frac{N(\text{H} \textsc{i}) + N(\text{H} \textsc{ii}) + 2N(\text{H}_2)}{A_v} = (1.76 \pm 0.06) \times 10^{21} \text{ atoms cm}^{-2} \text{ mag}^{-1} \tag{2}
\]

where the standard deviation of an observation of average weight is \(0.54 \times 10^{21}\) atoms cm\(^{-2}\) mag\(^{-1}\). A correction of 4 per cent has been applied to account for ionized hydrogen in the vicinity of the sample stars (Jenkins 1976). If the uncertainty in \(R\) is 0.2, the mean error in this ratio is raised to \(0.13 \times 10^{21}\) atoms cm\(^{-2}\) mag\(^{-1}\).

We have attempted to use equation (2) to obtain an independent measure of the extinction towards Maffei 1. Observations of \(^{12}\text{CO}\) and \(^{13}\text{CO}\) have been made to estimate \(N(\text{H}_2)\). The galactic H\textsc{i} survey by Weaver & Williams (1973) is used to derive \(N(\text{H} \textsc{i})\). The column density of ionized hydrogen in the direction of Maffei 1 is assumed to be negligible, since the fraction of the mass which is ionized along a line-of-sight through the entire galaxy is expected to be small.

### 4.2 Neutral Hydrogen Column Density

Weaver & Williams (1973) used the Hat Creek 85-ft telescope and a 35.5 arcmin beam to make an extensive survey of galactic neutral hydrogen between longitudes 10° and 250° and between latitudes \(-10°\) and \(+10°\). Their calibrated antenna temperature profiles can be used to derive the column density of H\textsc{i} in the direction of Maffei 1.

The four profiles which bracket the coordinates of Maffei 1 \((l = 135°.84, b = -0°.57)\) were magnified with an enlarger and measured with a planimeter. The integrated brightness temperature \(T_B\) was interpolated to be

\[
\int T_B(v)dv = \int \frac{T_A(v)}{\eta} dv = 3620 \pm 30 \text{ K km s}^{-1} \tag{3}
\]

where \(v\) is velocity, \(T_A\) the calibrated antenna temperature and \(\eta\) the efficiency factor due to radiation losses. The efficiency factor has been taken to be 0.957, based on the assumption that the emitting gas completely fills the beam (Williams 1973).

In order to convert the integral to a column density, it is necessary to correct for optical depth effects. We assume that the spin temperature of H\textsc{i} is a constant \(T_s\) along the line-of-sight to Maffei 1. Then

\[
N(\text{H} \textsc{i}) = 1.823 \times 10^{18} \int -T_s \ln \left[ 1 - \frac{T_B(v)}{T_s} \right] dv
\]

\[
N(\text{H} \textsc{i}) = 1.823 \times 10^{18} k \int T_B(v) dv \tag{4}
\]

where \(T_s\) is in K, \(v\) in km s\(^{-1}\) and \(N(\text{H} \textsc{i})\) in atom cm\(^{-2}\).

We have computed the optical depth correction factor \(k\) by numerically integrating the H\textsc{i} profile at \(l = 136°.0, b = -0°.5\) and comparing the result with the value obtained in the optically thin approximation. Based on discussions by Kerr (1968), Burton (1970) and Baker & Burton (1975) and on the peak temperatures observed in the vicinity of Maffei 1,
a value of $125 \pm 10$ K has been adopted for $T_s$. It should be noted that this is considerably larger than the peak temperatures of around 80 K observed directly towards Maffei 1. We find

$$k = 1.27 \pm 0.04.$$  

Applying this correction factor to (3) and converting to column density units,

$$N(H_\text{i}) = (8.39 \pm 0.24) \times 10^{21} \, \text{cm}^{-2}.$$  

Clearly, the assumption of a homogeneous medium of neutral hydrogen is a poor one. In actuality, the spin temperature appears to fluctuate from place to place (Dickey, Salpeter & Terzian 1979). However, lacking HI absorption measurements towards Maffei 1, it is not possible for us to do better. Fortunately, the optical depth correction is not overwhelming. It is hoped that the uncertainty due to temperature fluctuations is adequately accounted for by the error adopted for $T_s$.

It has been assumed in the discussion above that the emission from Maffei 1 itself does not significantly affect the galactic HI line profiles. The heliocentric velocity of the galaxy is $+15$ km s$^{-1}$ (RC2), near the range $-100 \leq V_{\text{LSR}} \leq +10$ occupied by galactic clouds of neutral hydrogen. However, observations by Spinrad et al. (1971) indicated an upper limit of only 0.1 K for the antenna temperature due to extragalactic HI.

### 4.3 Molecular Hydrogen Column Density

The molecular hydrogen column density cannot be observed directly, so must be inferred from observations of CO. The 2.60 mm $J=1-0$ transition of $^{12}$CO usually suffers from saturation problems, so it is necessary to base molecular hydrogen column densities on observations of $^{13}$CO. Consider a cloud which is optically thin to the 2.72 mm $J=1-0$ line of $^{13}$CO and which is in LTE with a uniform temperature $T$. Assuming the rates of stimulated emission and collisional de-excitation are negligible, adopting $T = 20$ K, approximating $h\nu \ll kT$, the column density of $^{13}$CO is given by the integral of the radiation temperature profile $T_R(v)$,

$$N(^{13}\text{CO}) = 1.048 \times 10^{15} \int T_R(v) \, dv$$  

where

$$T_R(v) = \frac{T_A^*(v)}{\eta_{\text{FSS}} \eta_c}$$  

and where $v$ is the velocity in km s$^{-1}$, $T_A^*(v)$ is the antenna temperature in K at velocity $v$ in the 2.72 mm line, corrected for atmospheric extinction, the antenna radiation efficiency, and rear spillover and scattering, $\eta_{\text{FSS}}$ is the efficiency factor for forward spillover and scattering, and $\eta_c$ accounts for coupling between the beam and the source (see Gordon & Burton 1976). From observations of ~75 local molecular clouds, Dickman (1978) has linked empirically the column density of $^{13}$CO to the visual extinction $A_v$:

$$\frac{N(^{13}\text{CO})}{A_v} = (2.5 \pm 0.2) \times 10^{15} \, \text{cm}^{-2} \, \text{mag}^{-1}.$$  

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The standard deviation of the observations was $1.25 \times 10^{15}$ cm$^{-2}$ mag$^{-1}$. Assuming that all of the hydrogen in CO clouds is molecular, equations (2) and (7) lead to

$$\frac{N(H_2)}{N(13CO)} = (3.5 \pm 0.2) \times 10^5. \quad (8)$$

Unfortunately, $^{13}$CO emission is often too weak to be observed. Lacking $^{13}$CO data, it is possible to get a rough idea of the column density of H$_2$ from $^{12}$CO antenna temperatures. Gordon & Burton (1976) claimed that clouds, although individually optically thick to $^{12}$CO, when observed as aggregates appear effectively optically thin, such that the signal from $^{12}$CO along a path through the Galaxy is directly proportional to the signal from $^{13}$CO. Specifically, they adopt $T_A^{12CO}/T_A^{13CO} = 3$. Blitz & Shu (1980) suggested that this value should be revised to 5.5 on the basis of observations by Solomon & Sanders (1979). In the limit that a cloud becomes optically thin to $^{12}$CO, the antenna temperature ratio should be set by the carbon isotopic abundance ratio. For terrestrial abundances, $T_A^{12CO}/T_A^{13CO}$ would be 89 (Audouze 1977). However, the $^{12}$C/$^{13}$C ratio in the local interstellar medium is uncertain. Values ranging from around 40 to near terrestrial have been measured (Wannier 1980).

We have detected the $J = 1 - 0$ transition of $^{12}$CO and have obtained an upper limit to the $J = 1 - 0$ transition of $^{13}$CO in the direction of Maffei 1. The observations were made on 1980 October 21, 22 and 24 (UT) with the 4.9-m antenna and uncooled double sideband receiver of the Millimeter Wave Observatory on Mount Locke in West Texas.* Instrumental details are summarized in Table 4. Observations were begun just before midnight local time and continued until dawn. Skies were clear during the entire run.

Position-switching was implemented to set the baselines. For the observations of Maffei 1, two nearby emission-free reference fields were chosen on the basis of a set of galactic CO survey profiles provided by Dr R. Cohen of Columbia University. One position in the galaxy was observed twice, once with each reference field, in order to check that neither offset position was contaminated. The nearby calibrated strong sources W3 and W3 (OH) were observed periodically as standards, both to assess the performance of the system and to accomplish absolute calibrations. The coordinates adopted for Maffei 1, W3 and W3 (OH) are listed in Table 5. Positions observed towards Maffei 1 and the locations of the offset fields are given in Table 6. Offset positions for W3 and W3 (OH) were 120 arcmin north of the sources.

Observations were made in cycles of the form ON-OFF-OFF-ON. Integration times were 5 min at each stage, totalling 20 min for the cycle. After each cycle, a chopper wheel calibration was run. The results were used to convert the voltage spectra to first-order zero air mass antenna temperature spectra (Penzias & Burrus 1973), which were then stored on tape. This process corrected for the radiation efficiency and rear spillover and scattering, as well as for the atmospheric extinction (to first order).

Antenna tips were done at the beginning and end of each session to facilitate second-order temperature corrections. The correction scheme developed by Kutner (1978), which assumes a two-layer atmosphere and allows for a sky temperature different from ambient, was implemented. This led to refinements of from 3 to 5 per cent.

After calibration, all observations of one position made on a given night were co-added, and a few bad channels edited. The baseline was straightened and normalized to zero by

*The Millimeter Wave Observatory is operated by the Electrical Engineering Research Laboratory of the University of Texas at Austin, with support from the National Aeronautics and Space Administration, the National Science Foundation and McDonald Observatory.
fitting a line by eye to the emission-free channels. A line intensity then was measured by integrating the signal between two specified frequency bounds.

Conversion of $\int T_A^* \, dv$ to $\int T_R \, dv$ ($T_R$ = the radiation temperature) was accomplished by comparing the calibrated peak antenna temperature in the W3 and W3 (OH) profiles with the standard peak radiation temperatures. It was assumed that W3, W3 (OH), and the emitting regions towards Maffei 1 all filled the beam (see below), so that $n_e = 1.0$. The peak radiation temperatures $T_R$ of W3 and W3 (OH) were taken to be $33.1 \pm 1.8$ and $25.5 \pm 1.0$, respectively, in $^{12}$CO, and $7.3 \pm 0.6$ and $7.6 \pm 1.1$, respectively, in $^{13}$CO. These values were computed from the peak antenna temperatures adopted by MWO using $\eta_{\text{FSS}} = 0.85 \pm 0.02$. Thus, to correct for forward spillover and scattering and residual errors in the antenna temperature calibrations, it was found necessary to multiply all of the $^{12}$CO intensities by $1.5 \pm 0.1$ and all of the $^{13}$CO intensities by $2.2 \pm 0.2$. The integrated line intensities computed in this way for the directions towards Maffei 1 are given in Table 6. Velocities of the components are also given.

The calibration uncertainty can be assessed by comparing the two observations of the southern Maffei 1 position, which were taken on two different nights and reduced independently. It appears that the external errors are of order 15 per cent. Much of the uncertainty may be due to pointing errors, which affect observations of both Maffei 1 and the standard sources.

In all of the $^{12}$CO observations of Maffei 1, two well-separated narrow emission lines were found at velocities (with respect to the LSR) of $-36$ and $-42$ km s$^{-1}$, presumably due to two clouds along the line-of-sight (Fig. 3). In order to at least approximately determine the spatial distribution of these clouds, we made $^{12}$CO observations at two positions. The first position was chosen to be that given in RC2 (Table 5), but because of a later pointing correction this turned out to be 0.2 arcmin E and 0.7 arcmin S. The second position chosen was 1.3 arcmin N of the RC2 position. Table 6 shows that the integrated brightness of the $^{12}$CO emission from the higher velocity cloud (B) is $2.8 \pm 0.4$ K km s$^{-1}$ and is insensitive to the 2 arcmin difference between our two chosen positions. Since the half-power beamwidth of the 4.9-m telescope is $\sim 2$ arcmin, this cloud effectively filled the beam as a uniform source. The lower velocity cloud (A), on the other hand, shows some structure over the beam area.

### Table 4. CO spectroscopy observational parameters.

<table>
<thead>
<tr>
<th>Date (UT) 1980</th>
<th>Oct 21</th>
<th>Oct 22</th>
<th>Oct 24</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transition</td>
<td>$^{12}$CO (1–0)</td>
<td>$^{12}$CO (1–0)</td>
<td>$^{13}$CO (1–0)</td>
</tr>
<tr>
<td>Frequency (GHz)</td>
<td>115.271201</td>
<td>115.271201</td>
<td>110.201370</td>
</tr>
<tr>
<td>Wavelength (mm)</td>
<td>2.60</td>
<td>2.60</td>
<td>2.72</td>
</tr>
<tr>
<td>Sideband</td>
<td>Lower</td>
<td>Lower</td>
<td>Upper</td>
</tr>
<tr>
<td>Beam size (arcmin)</td>
<td>2.2</td>
<td>2.2</td>
<td>2.3</td>
</tr>
<tr>
<td>Channel width (km s$^{-1}$)</td>
<td>0.65</td>
<td>0.65</td>
<td>0.68</td>
</tr>
<tr>
<td>Number of channels</td>
<td>128</td>
<td>128</td>
<td>128</td>
</tr>
<tr>
<td>Average system temperature (K)</td>
<td>3500</td>
<td>3300</td>
<td>2600</td>
</tr>
</tbody>
</table>

### Table 5. Adopted positions.

<table>
<thead>
<tr>
<th></th>
<th>$\alpha$ (1950)</th>
<th>$\delta$ (1950)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(h m s)</td>
<td>($^\circ$ ' '')</td>
</tr>
<tr>
<td>Maffei 1</td>
<td>02 32 36.0</td>
<td>+59 25 59</td>
</tr>
<tr>
<td>W3</td>
<td>02 21 50.9</td>
<td>+61 52 18</td>
</tr>
<tr>
<td>W3 (OH)</td>
<td>02 23 17.0</td>
<td>+61 39 00</td>
</tr>
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</table>
Table 6. CO observations of galactic clouds towards Maffei 1.

<table>
<thead>
<tr>
<th>UT Date 1980</th>
<th>Molecule</th>
<th>Position (relative to Maffei 1)</th>
<th>Offset</th>
<th>Central $v_{\text{LSR}}$ (km s$^{-1}$)</th>
<th>Exposure (hr)</th>
<th>Cloud A $v_{\text{LSR}}$ (km s$^{-1}$)</th>
<th>Cloud A $fT_Rd\nu^*$ (K km s$^{-1}$)</th>
<th>Cloud A $v_{\text{LSR}}$ (km s$^{-1}$)</th>
<th>Cloud B $fT_Rd\nu^*$ (K km s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oct 21</td>
<td>$^{12}\text{CO}$</td>
<td>0'.2 E 71'W</td>
<td>-20</td>
<td>1.7</td>
<td>-36.0 ± 0.1</td>
<td>5.1 ± 0.5</td>
<td>-42.3 ± 0.1</td>
<td>2.7 ± 0.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>0'.7 S 128'S</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oct 22</td>
<td>$^{12}\text{CO}$</td>
<td>0'.2 E 43'E</td>
<td>-40</td>
<td>2.0</td>
<td>-36.1 ± 0.1</td>
<td>6.8 ± 0.5</td>
<td>-41.8 ± 0.1</td>
<td>2.5 ± 0.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>0'.7 S 146'S</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oct 22</td>
<td>$^{13}\text{CO}$</td>
<td>1'.3 N 71'W</td>
<td>-40</td>
<td>2.0</td>
<td>-35.7 ± 0.1</td>
<td>10.0 ± 0.6</td>
<td>-40.2 ± 0.3</td>
<td>2.9 ± 0.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>129'S</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oct 24</td>
<td>$^{13}\text{CO}$</td>
<td>1'.3 N 71'W</td>
<td>-45</td>
<td>4.0</td>
<td>-</td>
<td>≤ 0.5</td>
<td>-</td>
<td>≤ 0.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>129'S</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Uncertainties do not include calibration errors. $T_R/T_A^*$ = 1.5 ± 0.1 for $^{12}\text{CO}$ and 2.2 ± 0.2 for $^{13}\text{CO}$. 

Galactic extinction towards Maffei 1.
Figure 3. The spectrum of $^{12}$CO towards Maffei 1 from observations on 1980 October 21. The centre of the beam was 0.2 E and 0.7 S of the nucleus of the galaxy. There appear to be two distinct molecular clouds along the line-of-sight. The dashed horizontal line marks the adopted baseline.

since the integrated brightness of the $^{12}$CO emission ranges from $5.1 \pm 0.5$ K km s$^{-1}$ to $10.0 \pm 0.6$ K km s$^{-1}$.

The large flux detected at position 2 for cloud A suggested that $^{13}$CO observations were feasible provided that $T_A^{13}\text{(CO)} \geq 0.1 T_A^{12}\text{(CO)}$. However, we detected no $^{13}$CO emission to an upper limit of $0.5$ K km s$^{-1}$ (three sigma) at position 2 over 4 hr of observing time, indicating that $T_A^{12}\text{(CO)}/T_A^{13}\text{(CO)} \geq 20$. The high value of this ratio indicates that both $^{12}$CO and $^{13}$CO may be optically thin. A lower limit to $N(H_2)$ can be derived by assuming that $T_A^{13}\text{(CO)} = 1/89 T_A^{12}\text{(CO)}$ and an upper limit by assuming $T_A^{13}\text{(CO)} = 1/20 T_A^{12}\text{(CO)}$. Adopting a total $^{12}$CO flux integral of $10.1 \pm 1.1$ K km s$^{-1}$ for the RC2 position of Maffei 1, we find, from (5),

$$(1.2 \pm 0.1) \times 10^{14} \leq N(13\text{CO}) \leq (5.3 \pm 0.6) \times 10^{14} \text{cm}^{-2}. \tag{8}$$

From the limits on $N(13\text{CO})$, equation (8) now yields

$$(4.2 \pm 0.4) \times 10^{19} \leq N(H_2) \leq (1.9 \pm 0.1) \times 10^{20} \text{cm}^{-2}. \tag{9}$$

4.4 THE EXTINCTION

Having derived $N(\text{H}1)$ and $N(H_2)$, it is now possible to estimate the galactic extinction of Maffei 1 using equation (2). It is necessary to make two assumptions regarding the nature of the interstellar medium along the line-of-sight. First, it is assumed that the gas-to-dust ratio is, on average, normal along the path to Maffei 1. The path is so long that small-scale fluctuations are probably smoothed out. However, the effects of a radial metal abundance gradient are uncertain. If significant reddening were occurring at large galactocentric radii and if the gas-to-dust ratio increases with radius, then the extinction computed from equation (2) would be too high. However, much of the extinction appears to occur within 3 kpc of the Sun, i.e. within a narrow range of galactocentric radii (8.5 to 11 kpc) (see Buta, McCall & Uomoto 1980).
The column density of hydrogen implied by the results above indicates that, in order to derive $A_v$ for Maffei 1, equation (2) must be extrapolated. Having corrected for saturation effects, an extrapolation is perfectly legitimate provided that no cloud along the line-of-sight has a volume density severely in excess of that for the densest clouds used to construct the relation. If this were the case, the column density of H$_2$ could be perturbed by molecular chemistry and the optical absorption efficiency could be altered by accretive grain growth. Fortunately, the high value of $T_A^*$(12CO)/$T_A^*$(13CO) indicates that high density clouds occupy little of the mass along the path to Maffei 1.

We now feel justified in applying equation (2) to derive the extinction of Maffei 1. Adopting $N$(H i) = $(8.39 \pm 0.24) \times 10^{21}$ cm$^{-2}$, $N$(H II) = 0, and $(4.2 \pm 0.4) \times 10^{19}$ $\lesssim N$(H$_2$) $\lesssim (1.9 \pm 0.1) \times 10^{20}$ cm$^{-2}$, then

$$4.81 \pm 0.38 \lesssim A_v \lesssim 4.98 \pm 0.39.$$ 

We adopt $A_v = 4.9 \pm 0.4$ mag.

5 Discussion

5.1 SUMMARY OF $A_v$ DETERMINATIONS

With the results of this paper, there are now seven estimates available for the extinction towards or in the vicinity of Maffei 1. Table 7 summarizes the methods involved and the values of $A_v$. We discuss in this section the relative merits of each method and derive a final value of $A_v$.

5.1.1 Comparison of the continuum slope of the nuclear spectrum of Maffei 1 with M31 and NGC 3379

Spinrad et al. (1971) infer from the presence of the Na i D lines and TiO bands that Maffei 1 is probably a giant early-type galaxy. On the assumption that the unreddened nuclear spectral

<table>
<thead>
<tr>
<th>Table 7. Summary of extinction estimates.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Method</td>
</tr>
<tr>
<td>(a) Comparison of spectral energy distributions</td>
</tr>
<tr>
<td>(b) Application of $Q$-method to 111 B Stars within 1° of Maffei 1</td>
</tr>
<tr>
<td>(c) Application of $Q$-method to nebulous blue star 5.6 arcmin north-east of Maffei 1</td>
</tr>
<tr>
<td>(d) Application of $Q$-method to early-type stars near IC 1805</td>
</tr>
<tr>
<td>(e) Counts of M stars near Maffei 1</td>
</tr>
<tr>
<td>(f) Integrated colour index</td>
</tr>
<tr>
<td>(g) Gas-to-extinction ratio</td>
</tr>
<tr>
<td>Adopted</td>
</tr>
</tbody>
</table>

References

1. Spinrad et al. (1971); 2. Kohoutek & Haug (1972); 3. Buta, McCall & Uomoto (1980); 4. Nandy & Smriglio (1973); 5. this paper.
energy distribution of Maffei 1 is identical in shape to that of normal giant E or Sb systems like NGC 3379 or M31 in the wavelength range $0.38 < \lambda < 3.3 \mu m$, they derived a visual extinction $A_v = 5.2 \pm 0.2$ mag. Unless the assumption of similar spectral energy distributions is in serious error, this should be a reasonable estimate of the total extinction, galactic plus internal, affecting the nuclear spectrum. Internal absorption is discussed separately below.

5.1.2 Application of the Q-method to early-type stars surrounding Maffei 1

Kohoutek & Haug (1972) studied the variation of visual extinction with distance from photographic $UBV$ photometry of 111 B stars within a one degree radius centred on Maffei 1. They found that the visual extinction rose rapidly out to $r = 1.5$ kpc, but levelled off to a near constant value of $3.2$ mag from 1.5 to 7 kpc. Because of the patchy obscuration in this area, they employed star counts to correct the extinction estimate for each star to the conditions near Maffei 1. This led to $A_v = 3.1 \pm 0.4$ mag, which is significantly lower than that derived from the preceding method. One obvious possible cause of this discrepancy is that significant additional galactic absorption exists beyond $r = 7$ kpc, the distance limit of Kohoutek & Haug’s analysis.

5.1.3 Application of the Q-method to a nebulous blue star near Maffei 1

Buta et al. (1980) identified a nebulous blue object 5.6 arcmin north-east of Maffei 1 to be a B3 V star surrounded by a reflection nebula. A colour excess of 1.04 mag was derived, leading to $A_v = 3.33$ mag ($R = 3.2$) and a distance of 2.9 kpc. The value of the extinction is close to the mean value $A_v = 2.8$ mag derived by Kohoutek & Haug (1972) at the same distance. Because the nebulous star is close to Maffei 1, its reddening provides a lower limit to the extinction for Maffei 1 itself. If most of the reddening of the star is due to foreground galactic extinction and not to a significant enhancement of dust in its own vicinity, then Maffei 1 must suffer at least $3.3$ mag of extinction.

5.1.4 Application of the Q-method to early-type stars in the vicinity of IC 1805

Nandy & Smriglio (1973) presented studies of OB stars in a 2 degree$^2$ area centred on the bright emission nebulosity IC 1805, which is 1°.9 nearly due north of the Maffei galaxies. They found that the visual extinction rises rapidly to $3.4$ mag at $r \approx 1$ kpc, and then varies only slowly from 3.4 to 3.7 mag for $1 \leq r \leq 3$ kpc, with a scatter of $\pm 0.5$ mag due principally to the patchy obscuration in this area. This trend is similar to that found by Kohoutek & Haug (1972) over the same range of distances towards Maffei 1, but the mean level is $\sim 1$ mag higher. Unfortunately, only two stars in the Nandy & Smriglio analysis have $r > 4$ kpc. The most distant, at 5.5 kpc, has $A_v = 5.2$ mag. Unless this star is affected by a local dust cloud of enhanced density relative to the field, there is a suggestion of a rapid rise in visual extinction for $r > 4$ kpc to a level consistent with the high value derived here and by Spinrad et al. (1971) for Maffei 1. However, this trend, if significant, can only apply to the direction of IC 1805 and is not necessarily valid for the direction of the Maffei galaxies.

5.1.5 Counts of M stars in the field of Maffei 1

The variation of interstellar extinction with distance was also derived by Nandy & Smriglio (1973) by comparing counts of M stars in a 3 degree$^2$ area centred on Maffei 1 with counts in a more transparent region 2 degrees away. This method yields the extinction in the Maffei...
region relative to that in the comparison region. The counts indicate that the absorption is significantly higher in the Maffei region, particularly for infrared magnitudes fainter than 10. Assuming that the distance dependence of visual interstellar absorption for the comparison region was essentially that derived from the OB stars near IC 1805, Nandy & Smriglio found that $A_V$ varies from 3.6 to 4.6 mag for $1 \text{kpc} \leq r \leq 4.2 \text{kpc}$ in a linear manner with no sign of levelling off. One can then adopt their limiting value, $A_V = 4.6 \pm 0.7$ mag, as a lower limit for the extinction towards Maffei 1. The large mean error is due to the scatter in the absolute magnitudes of the M stars used and to the error in the mean absorption curve for IC 1805.

5.1.6 Colour index of Maffei 1 from BV multi-aperture photometry

As was shown in Section 3, the integrated colour index of Maffei 1 is $2.35 < (B-V) < 2.38$, and the galactic reddening is $1.49 < E(B-V) < 1.54$ if Maffei 1 is in every respect normal compared to other galaxies of similar Hubble type. This method yields a colour excess in excellent agreement with that derived by Spinrad et al. (1971). Both methods assume that the intrinsic colour of the galaxy is not unusual for its type. If Maffei 1 were abnormally luminous and/or metal rich, the adopted intrinsic colour would be too blue, and the extinction overestimated.

5.1.7 Correlation between total column density of hydrogen and extinction

As shown in Section 4, the total column density of hydrogen towards Maffei 1 leads to $A_V = 4.9 \pm 0.4$ mag. The method has three advantages over the others:

1. It does not depend on assumptions about the intrinsic properties of Maffei 1.
2. It does not involve direct measurements of Maffei 1 itself, and hence cannot be affected by internal absorption within the galaxy.
3. It accounts for extinction arising along the entire path through the Galaxy, i.e. there is no distance limit involved.

However, the method must rely on the assumption that the dust-to-gas ratio is normal in the clouds responsible for most of the extinction. The main source of uncertainty probably lies in the correction of neutral hydrogen observations for optical depth effects.

5.2 Internal absorption within Maffei 1

Extinction estimates based on the photometric properties of Maffei 1 could be affected by internal absorption. If the arcs of obscuration observed near the centre of Maffei 1 are intrinsic to the galaxy, then internal extinction may be significant, and the external extinction overestimated.

Heidmann, Heidmann & de Vaucouleurs (1971) have derived statistical relations which can be used to estimate how much internal absorption might be present. Since the inclination of Maffei 1 is not known, it is necessary to use the axis ratio formula (to correct blue light to a face-on orientation),

$$A_B(i) = \alpha(T) \log R_{25}$$

(9)

where $R_{25}$ is the isophotal axis ratio at $\mu_B = 25.0 \text{mag} \text{arcsec}^{-2}$ and $\alpha$ is a factor depending on the Hubble stage $T$ (coded on the RC2 numerical scale). For $T < -4$, $\alpha(T) = 0$, but for $-3 < T < -1$, $\alpha(T) = 0.2(T + 4)$. According to RC2, $\log R_{25} = 0.07 \pm 0.07$ for Maffei 1, so
that for the range of types $-3 \leq T \leq -1$ these relations would indicate $0.01 \leq A_B(i) \leq 0.04$ mag.

However, the axis ratio in blue light is not well determined and, in any case, refers to the very central part of the galaxy. In red light the axis ratio is close to $\log R = 0.15$. Using this value, $A_B(i) \leq 0.09$ mag, and the integrated colour of Maffei 1 could be intrinsically reddened by up to $E(B-V) = 0.02$ mag. This shows that inclination is probably not seriously affecting the colour excess estimates of Sections 5.1.1 and 5.1.6.

The only remaining question is whether the internal obscuration of Maffei 1 can be much in excess of the mean for its type, particularly near the centre. This is difficult to estimate, but to illustrate that such absorption does not have a serious effect on integrated colours, we look at an extreme example of internal absorption within a relatively normal early-type spiral, NGC 4826. This galaxy, of type Sab ($T = 2$), is well known for a striking, large arc of absorption near the centre, and so has been christened the ‘blackeye’ galaxy. It has a corrected colour index $(B-V)_0 = 0.75$ according to RC2. By comparison, the table of fully-corrected mean colours given by de Vaucouleurs (1977) shows that $(B-V)_T = 0.70$ for $T = 2$, indicating that, as expected, NGC 4826 is slightly redder in integrated light than normal due to the absorption by the dust lane. Nevertheless, the net effect on the integrated colour is slight; for Maffei 1, such a dust lane would lead to an error of $0.05$ mag in $E(B-V)$, or $0.18$ mag in $A_V$.

Since observations of Maffei 1 were confined to the central area, it is perhaps more relevant to look at the contrast between the colour of the dust lane and the integrated colour of NGC 4826. Detailed surface photometry by Simkin (1967) shows that the colour at the dust lane minimum in the photoelectric profiles is $(B-V) = 0.98$. Integrated light photometry given in RC2 (uncorrected) indicates that $(B-V)_T = 0.84 \pm 0.03$. The excess in colour of the dust lane over the integrated light is 0.14 mag. If Maffei 1 were similarly affected, $A_V$ would have been overestimated by about 0.5 mag.

5.3 THE EXTINCTION

Observations of foreground stars appear to lead to underestimates of the extinction towards Maffei 1 due to distance limitations. Therefore, we have decided to adopt an extinction based only on photometry of the galaxy and on the line-of-sight hydrogen column density. The final adopted value of the extinction is given in Table 7. The weights assigned to the separate determinations used in computing the mean are also given in the table. Note that the two photometric estimates are not totally independent, so they have been averaged with equal weight. The uncertainty given for $A_V$ is simply half the range between the photometric average and the value based on the gas column density. Henceforth, we will assume $A_V = 5.1 \pm 0.2$ mag.

5.4 THE DISTANCE AND GROUP MEMBERSHIP

At the present time there are five fully developed methods that can be used to derive the distance to a galaxy earlier in Hubble stage than S0/a. These are:

(a) the colour–absolute magnitude effect (Sandage & Visvanathan 1978)
(b) the magnitude–colour–surface brightness relation for ‘main-sequence’ ellipticals and lenticulars (Michard 1979a, b)
Galactic extinction towards Maffei 1

(c) the luminosity–central velocity dispersion relation (Faber & Jackson 1976; de Vaucouleurs & Olson 1982)
(d) the diameter of an inner ring structure (Buta & de Vaucouleurs 1982); and
(e) the apparent luminosity function of globular clusters (Hanes 1977).

Since we have assumed an intrinsic colour to get the extinction towards Maffei 1, methods (a) and (b) cannot be used; they have low precision, in any case. There is no evidence, even in the infrared, that Maffei 1 possesses an inner ring structure, nor has a halo of globular clusters been detected surrounding it, so that methods (d) and (e) also cannot be used. Fortunately, method (c) can be applied to Maffei 1 once its total magnitude and central velocity dispersion are known. In particular, de Vaucouleurs & Olson (1982) have derived for visual light

\[-M_T^0(V) = 20.35 + 8.5 \log \sigma_v - 2.3\]  \hspace{1cm} (10)

where \(\sigma_v\) is the central velocity dispersion in \(\text{km s}^{-1}\) and \(M_T^0\) is the absolute magnitude. If both \(V_T^0\) and \(\sigma_v\) are known sufficiently accurately, this method is capable of yielding distance moduli with mean errors of 0.4 to 0.6 mag.

Unfortunately, \(\sigma_v\) is poorly known for Maffei 1. Spinrad et al. (1971) estimated \(\sigma_v\) to be \(200 \pm 50 \text{ km s}^{-1}\) from \(60 \text{ A mm}^{-1}\) dispersion slit spectra. If Maffei 1 is a normal elliptical galaxy, \(V_T = 11.4 \pm 0.1\) and, with \(A_v = 5.1 \pm 0.2\), \(V_T^0 = 6.3 \pm 0.2\). Equation (15) then yields a distance modulus \(\mu_0(\sigma_v) = 26.65 \pm 1.00\), or \(\Delta = 2.1^{+1.3}_{-0.8} \text{ Mpc}\). The error includes the errors in \(\sigma_v\), \(V_T^0\), the cosmic scatter (0.2 mag) and the zero point error of the distance scale.

<table>
<thead>
<tr>
<th>Object</th>
<th>Type</th>
<th>l</th>
<th>b</th>
<th>(B_T^0)</th>
<th>(A_B)</th>
<th>(V_T^0) (\text{km s}^{-1}))</th>
<th>(\mu_0)</th>
<th>Ref.</th>
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<tr>
<td>Maffei 1</td>
<td>E</td>
<td>135\°84</td>
<td>-0\°57</td>
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<td>6.6</td>
<td>223</td>
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<td>Maffei 2</td>
<td>Sb</td>
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<td>-0.33</td>
<td>...</td>
<td>8.1</td>
<td>208</td>
<td>28.5</td>
<td>2</td>
</tr>
<tr>
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<td>138.18</td>
<td>+10.58</td>
<td>7.86</td>
<td>1.25</td>
<td>228</td>
<td>27.34</td>
<td>4</td>
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<tr>
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<td>+16.01</td>
<td>10.92</td>
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<td>151</td>
<td>27.33</td>
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<tr>
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<td>+11.24</td>
<td>10.58</td>
<td>1.08</td>
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</tr>
<tr>
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<td>142</td>
<td>+41</td>
<td>8.72-13.02</td>
<td>0.3</td>
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<td>N2366</td>
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<td>10.67</td>
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<td>0.38</td>
<td>259</td>
<td>27.09</td>
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</tr>
</tbody>
</table>

Methods and References: (1) this paper (luminosity–central velocity dispersion relation); (2) Spinrad et al. 1973 (uncorrected sizes of HII regions); (3) Bottinelli et al. 1971 (integrated HI properties); (4) de Vaucouleurs 1978b, Table 7 (secondary indicators); (5) de Vaucouleurs 1979, Table 1 (luminosity index plus tertiary indicators); (6) Bottinelli et al. 1980 (21-cm line width plus tertiary indicators).

* A complete list of potential members is given by de Vaucouleurs (1975).
(0.2 mag). On the other hand, if Maffei 1 is an S0 galaxy with unusually high surface brightness, then \( V_T = 12.0 \pm 0.2, \sigma_T = 6.9 \pm 0.3 \) and \( \mu_0(\sigma_T) = 27.25 \pm 1.00 \) (including uncertainty of Hubble type). It appears that Local Group membership is excluded. Most of the uncertainty in this estimate is due to \( \sigma_T \) and not to \( V_T \) or \( A_V \). Clearly, an improved determination of the central velocity dispersion of the galaxy is needed.

Bottinelli et al. (1971) and van den Bergh (1971b) have suggested that both Maffei 1 and 2 are low latitude members of the nearby Ursa Major–Camelopardalis Cloud, which is described by de Vaucouleurs (1975). This cloud is comprised of about a dozen galaxies in the distance range 2–4 Mpc, including the low latitude IC 342 group and the higher latitude M81 and NGC 2403 groups. Data for all suspected members with known distances are compiled in Table 8. If Maffei 1 is an elliptical galaxy at \( \Delta = 2.1 \) Mpc, then our analysis confirms the suspicions that Maffei 1 is a member of this cloud. It may be the only non-spiral, massive member and, together with NGC 5102 in the Centaurus Group (de Vaucouleurs 1979), is one of the two nearest giant early-type galaxies.

We note that globular clusters have not been detected around Maffei 1. de Vaucouleurs (1978a) has shown that the luminosity function of galactic globular clusters is Gaussian with a mean \( M_v(\sigma) = -7.3 \) and dispersion \( \sigma = 1.0 \) mag. If Maffei 1 were at a distance of 1.0 Mpc and if the extinction is \( A_V = 5.1 \) mag, then the mean apparent magnitude of globular clusters would be \( m_v = 22.8 \). This suggests that some globular clusters would be visible on deep IIIa-J or \( V \) plates, and the observable part of the luminosity function might well extend fainter than the mean in the infrared. On the other hand, if the distance modulus is 26.7, as suggested by our analysis, then the mean apparent magnitude of the globular cluster system would be \( m_v = 24.5 \), which would be very difficult to reach with ground-based telescopes. If the brightest globular clusters occur at \( M_v = -10 \), then these should be observable at \( m_v = 20.1 \) or 21.8 at \( \Delta = 1.0 \) and 2.1 Mpc, respectively.

6 Conclusions

The important results of this paper are as follows:

(1) The galactic extinction towards Maffei 1 is \( A_V = 5.1 \pm 0.2 \) mag. Estimates based on a comparison of the continuum spectrum and integrated colour of the centre of Maffei 1 with other galaxies of similar Hubble type agree well with the value derived from the total galactic hydrogen column density and its correlation with extinction. Analyses of field stars surrounding Maffei 1 yield lower extinctions, probably because of distance limitations.

(2) The total magnitude of Maffei 1, based on multi-aperture photometry, is in the range \( 11.4 \leq V_T \leq 12.2 \). The uncertainty is due to the imprecision of the Hubble type and the small size of the apertures relative to the true galaxy size. Maffei 1 appears to be of somewhat high surface brightness compared to other early-type galaxies. The galaxy would be least abnormal if it were an E system.

(3) The inner parts of Maffei 1 follow an \( r^{1/4} \) law. The effective radius of the spheroidal component is \( r_e \sim 2–3 \) arcmin. If Maffei 1 is an elliptical galaxy, the isophotal diameter must be \( \sim 15 \) arcmin.

(4) The total magnitude estimates (which are fainter than \( V_T = 11.0 \) derived by Spinrad et al. 1971), when combined with a revised calibration of the Faber–Jackson relation, lead to a distance of \( \Delta = 2.1^{+0.3}_{-0.8} \) Mpc if Maffei 1 is an E galaxy, or \( 2.8^{+1.1}_{-1.0} \) Mpc if Maffei 1 is an SO galaxy. We conclude that Maffei 1 is probably not a member of the Local Group, but, instead, is a likely member of the nearby Ursa Major–Camelopardalis Cloud. The separation of Maffei 1 from IC 342 may be as small as 0.6 Mpc.
Our best evaluations for the most important properties of Maffei 1 are summarized in Table 9.

Acknowledgments

We thank W. L. Peters and L. G. Mundy for their valuable assistance with the CO observations and data reductions and R. Cohen for supplying us with galactic survey CO profiles in advance of publication. RJB acknowledges the support of a David A. Benfield Fellowship from the University of Texas and a USA—Australia Fulbright Scholarship from the Australian—American Educational Foundation during various phases of this work. MLM is grateful for support by the Natural Sciences and Engineering Research Council of Canada.

References


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Maffei 1 shows a large velocity residual from the ridge-line solution for the motion of the local standard of rest relative to the centroid of the Local Group, which led Yahil, Tammann & Sandage (1977 *Astrophys. J.*, 217, 903) to conclude also that it is not a member of the Local Group.