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PROBING THE EXTINCTION LAW AND GAS-TO-DUST RATIO M31 VIA GLOBULARS BEHIND THE DISK

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Abstract. We use the Catalogue of M31 Globular Clusters and Globular Clusters Candidates, compiled by Barmby (2000), containing 400 M31 globular clusters and candidates. We reduce this list to a sample of 41 globular clusters that have: (i) UBVRIK photometry, (ii) HI data, (iii) reliable [Fe/H] and (iv) reliable extinction as determined by us. For determining the intrinsic colours we used the evolutionary synthesis models for globular clusters by Kurth *et al.* (1999). The mean total-to-selective ratio in M31 in terms of the analytical formula by Cardelli *et al.* (1989) is found to be R_V 2.7 ± 0.2. Using data from 21 cm observations of M31 we got the HI column densities and obtained N(HI)/Av $\sim 9 \times 10^{20}$ atoms cm^{-2} mag^{-1} but varying with the radius, indicating possible supersolar metallicity toward the centre of M 31 galaxy.

1. Introduction

The understanding of true opacities in galactic disks is extremely important because of its impact on various extragalactic problems. An accurate knowledge of the reddening in the galactic disks is very helpful in building gas-and-dust distributions and stellar statistics.

M31 is one of the most studied galaxies because of its proximity. Its distance of only 0.7 Mpc allows precise spectroscopy and photometry of M31 globular clusters. Several hundred globulars is a very promising number not only for comprehensive statistical studies but also for a search for objects lying behind the greatest curtain on the sky.

The globulars in M31 have been used to test the quality of the models, assuming Galactic extinction law (Ivanov & Nedialkov, 1997). Here we assume that the models are correct and check the variance of the extinction law in M31. Recently, Nedialkov & Veltchev (1999) derived a mean gas-to-dust ratio in M 31 in star-formation regions somewhat larger (3.8) than the canonical Galactic value (3.1). In this paper we present a study of M31 globular cluster system, which helps us to derive the M31 extinction law as well as accurate gas-to-dust ratios. We combine reliable spectroscopically determined metallicities with UBVRIK photometry to obtain the absorption distributions and to test the reddening law in M31. We also obtain N(HI)/A_V using HI column densities from Brinks & Shane (1984).

2. Data

In this work all observational parameters of the globular clusters are obtained from the *Catalogue of M31 Globular Clusters and Globular Cluster Candidates*, compiled by P. Barmby (version from February, 2000). Originally, the catalogue contained about 400 globulars, having photometry data, determined [Fe/H] and coordinates. The first step was to select the objects with spectroscopically determined [Fe/H] and reliable photometry in at least UBVRIK bands.

In order to use model colours from Kurth *et al.* (1999) we had to convert the catalogue data for [Fe/H] into Z. We did this assuming that solar abundance ratios can be applied to M31 responsibly. This assumption, based on the Padova Group (1999) exact values, leads to

$$[Fe/H] = \lg(Z/X) + 1.596548 \tag{1}$$

Taking into consideration the following two simple relations

$$X = 1 - Y - Z = 0.77 - 3.25Z \tag{2}$$

$$Y = 0.23 + 2.25Z \tag{3}$$

The final conversion formula for Z comes to be

$$Z = \frac{0.77.10^{[Fe/H]-1.596548}}{3.25.10^{[Fe/H]-1.596548} + 1} \tag{4}$$

3. M31 Extinction Law

3. 1. MODEL COLOURS AND EXTINCTIONS

After we determine Z we can obtain the intrinsic colours of the globular clusters using the evolutionary model colours from Kurth (1999). Unfortunately, we had model colours for only six values of Z for which the authors calculated the temporal evolution of the UBVRIK colours. We performed interpolation in Z to determine how the colours of our clusters evolve with age. In Fig. 1 B-V is given as a function of Z and log *t*.

Using the photometry data from the catalogue and the model colours we obtain the following extinctions: $E_{X-Y} = (X-Y) - (X-Y)_0$, where $(X-Y)$ is $(U-B)$, $(B-V)$, $(V-R)$, $(V-I)$, $(V-K)$. Since for a given Z the model colours are calculated for 34 different ages, we actually get 34 different extinctions in each colour. This result accounts for the fact that different ages means different spectral distributions amounting to age-dependent reddening.

3. 2. ABSORPTION AND A_λ/A_V

In the previous section we determined E_{X-Y} which allows us to determine A_λ (where λ is the centre of the pass band) since $E_{X-Y} = A_X - A_Y$. These expressions give us 34 values for A_λ depending on the age of the cluster. At the same time we obtain A_V using the relation

$$A_V = E_{B-V}.R_V \tag{5}$$

Here R_V is a free parameter that gives one of the forms of the extinction law. Firstly, we do not assume any particular value for R_V. Instead, we vary it from 2.0 to 6.5 with a step of 0.1. When entered into equation (5) and the 34 possible different values for E_{B-V} have been taken into account we get a set of 1564 values for A_V.

The above derived A_λ/A_V we compare with the average R_V-dependent extinction law from Cardelli *al.* (1989) which is in the form

$$\langle A_\lambda/A_V\rangle = a(x) + b(x)/R_V \tag{6}$$

Here $a(x)$ and $b(x)$ are functions of λ^{-1}, where λ is the centre of the pass band in the Cousins photometric system. It is important to consider the spectral dependence of the parameters which the authors deal with by giving two expressions for $a(x)$ and $b(x)$ for the infrared and optical.

1)For the Infrared $0.3\mu m^{-1} \leq x \leq 1.1\mu m^{-1}$

$$a(x) = 0.574x^{1.61} \qquad \text{and} \qquad b(x) = -0.527x^{1.61} \tag{7}$$

2)In the Optical $1.1\mu m^{-1} \leq x \leq 3.3\mu m^{-1}$ and $y = x - 1.82$

$$\begin{aligned} a(x) = 1 + 0.17699y - 0.50447y^2 - 0.02427y^3 + 0.72085y^4 + \\ +0.01979y^5 - 0.77530y^6 + 0.32999y^7 \end{aligned} \tag{8}$$

$$\begin{aligned} b(x) = 1.41438y + 2.28305y^2 + 1.07233y^3 - 5.3843y^4 - \\ -0.62251y^5 + 5.30260y^6 - 2.09002y^7 \end{aligned} \tag{9}$$

We vary R_V in the same limits as before. We obtain the extinction law in two independent ways and get two sets of points depending on the age of the clusters and varying with the free parameter R_V. By comparing the two extinction laws we determine the error distribution as a function of age and R_V. In Fig. 2 is shown the plot of A_λ/A_V versus λ^{-1} for two globulars, corresponding to three different ages (including the one with smallest residual) and extinction law parametrized for total–to–selective ratio R_V equal to 2.7 and 5.4 respectively.

Using the smallest residuals along the A_λ/A_V axis (see Fig. 2) as a criterion for determining R_V and the ages of the clusters, we obtain a mean R_V of 2.72 (Fig. 5), which well corresponds to the polarimetry results (Martin & Shawl, 1979) of previous studies. Notably, there are several clusters in our selection with a few extrema in the error corresponding to different ages and R_V (Fig. 3 and Fig. 4), which might be reasonably interpreted either as young and bright objects behind the disk or as old ones in front with small extinction.

It is particularly interesting to look at the A_V histogram (Fig. 5), where one can notice a slightly bimodal nature of the distribution. Our selection is based on the presence of HI data in these lines of sight (Fig. 6). The sample of objects we use is selected by this criterion and hence the A_V distribution shows mostly clusters behind the disk. The large measured values for A_V suggest that most clusters lie behind the M31 disk. Considering this, we can say that this A_V distribution probably reflects the presence of clusters in front of the disk as well as some behind.

Although we do not have many clusters between us and the M31 plane (observationally), the sample that we have is statistically significant to build R_V distribution depending on the distance between the cluster and the centre of the galaxy R, as well as to study the gas-to-dust ratio in M31 (Section 4).

3. 3. AGES

Minimal error between the two extinction laws (as discussed in the previous section), gives also the ages of the clusters. The histograms of the obtained ages and corresponding R_V and A_V are shown on Fig. 6. Using this method we found several candidates for young clusters which are visible to us because they lie along lines of sight with smaller absorption. The more unlikely option is that these clusters are located in average absorption region but are intrinsically brighter. However, we think that the used technique might not be that sensitive with respect to the age. In fact in the error bar we can virtually have clusters with any age (Fig. 3).

4. A_V and the Gas-to-Dust Ratio

Using the values for A_V we obtained above and the HI column densities, determined by Brinks & Shine (1984) from 21cm radio observations, we derived the gas-to-dust ratio in M31. We give the positions of the sample clusters on the map of atomic hydrogen, provided also by Brinks & Shane (1984) in Fig. 6. The corresponding R_V and A_V are shown in Fig. 7, and a histogram of the obtained gas–to–dust ratios - in Table 1. and their distribution in Fig. 8. The two dashed lines on the plot in Fig. 7 bound the region of the plot where the Galactic gas-to-dust ratios vary. On the plot the triangles represent globulars typical for M31 and the circles are objects with smaller N(HI)/Av $\sim 9 \times 10^{20}$ atoms cm^{-2} mag^{-1} than the average for the Milky Way N(HI)/Av $\sim 15 \times 10^{20}$ atoms cm^{-2} mag^{-1} . From the column densities and calculated A_V we obtain N(HI) vs. A_V. It is convenient to use this data to plot $N(HI)/A_V$ versus distance to the centre (Fig. 9). Our plot is a confirmation of the

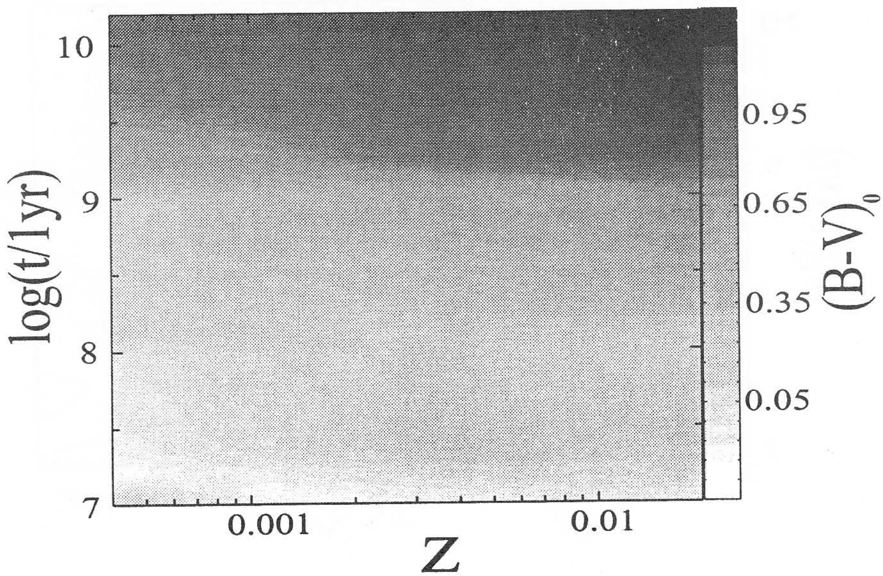

Fig. 1: Intrinsic $(B-V)_0$ color of globular cluster as function of metallicity and age.

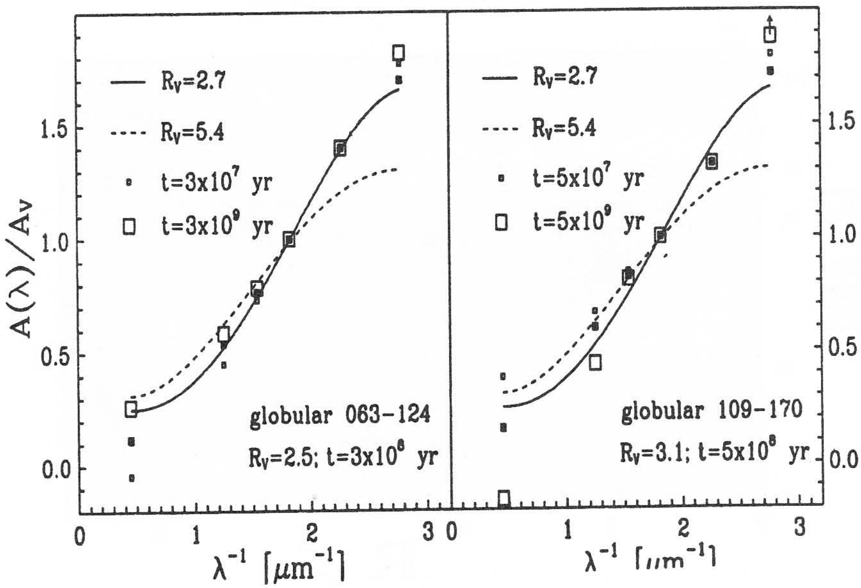

Fig. 2: Example of extinction law (CCM) optimization for two with fixed metallicity - 063-124 (right) and 109-170 (left).

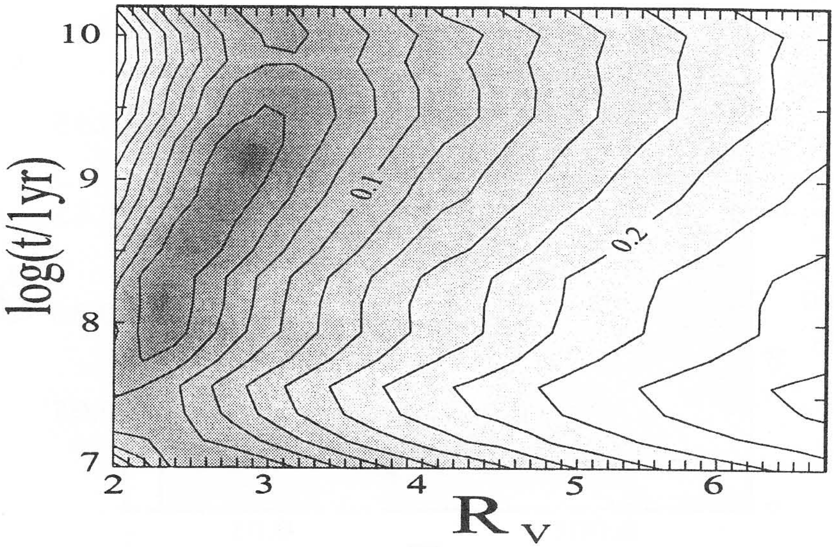

Fig. 3: R.M.S. of the residuals from the extinction curves as a function of the total-to-seelective extinction ratio (X-axis) and age (Y-axis). Typical example (cluster 109-170 from Fig. 2) of residuals with a few minima. Note the weak dependence of r.m.s. on the age.

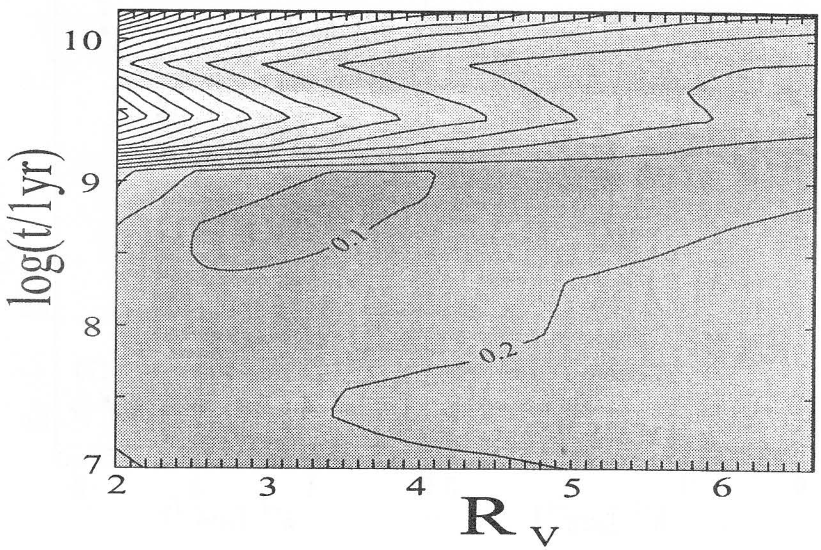

Fig. 4: Same as Fig. 3. Typical example (cluster 063-124 from Fig. 2) of residuals with well defined minimum.

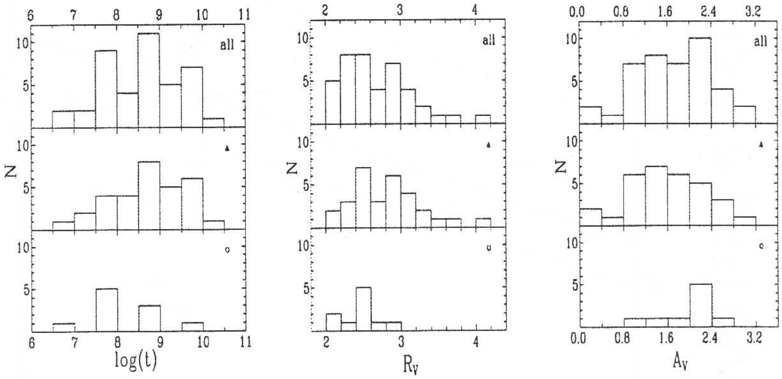

Fig. 5: Distribution by age (left), extinction (middle) and total-to-selective ratio (right) for 43 globulars, candidates to lie behind the disk of M31.

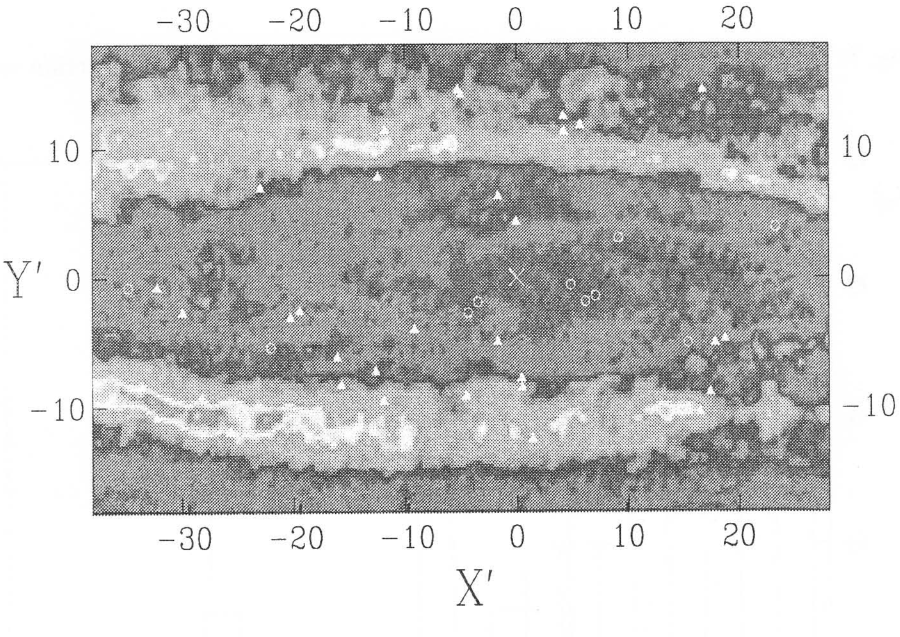

Fig. 6: Rectangular coordinates of the 43 globulars (relative to the galaxy centre), candidates to lie behind the disk of M31 galaxy. 33 globulars indicating "Galactic" gas-to-dust ratios are represented with filled white triangles and the rest - with white open circles. The positions are superimposed over the HI map (Brinks & Shane, 1984).

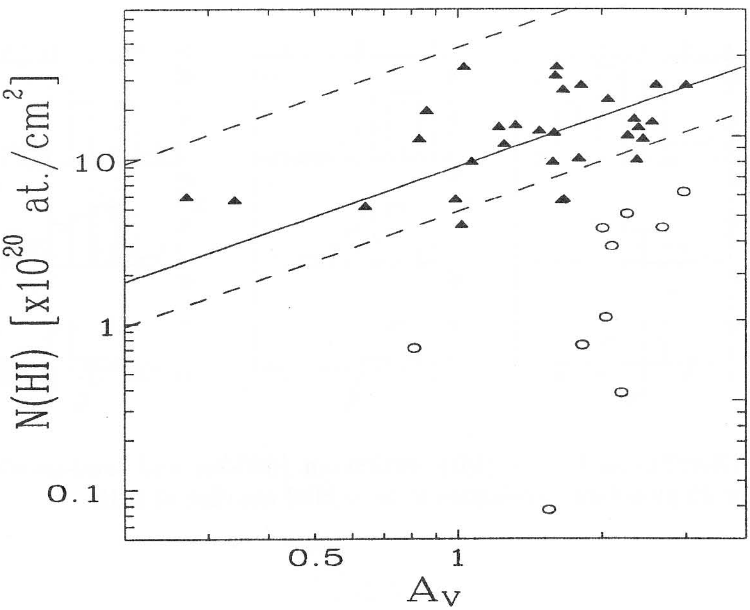

Fig. 7: HI column densities (Brinks & Shane, 1984) versus derived extinction values.

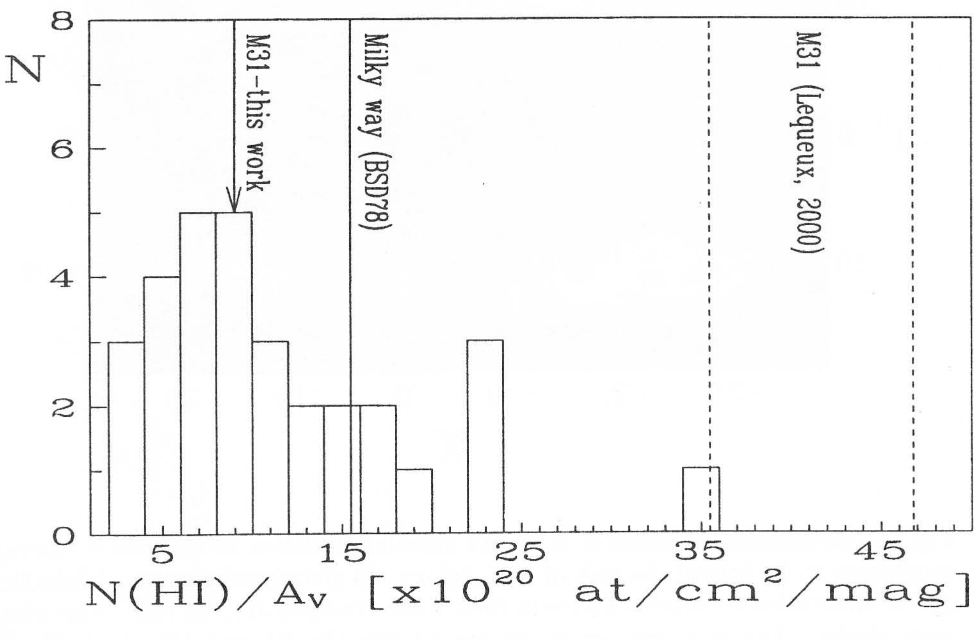

Fig. 8: Distribution by atomic gas-to-dust ratio for 33 globulars.

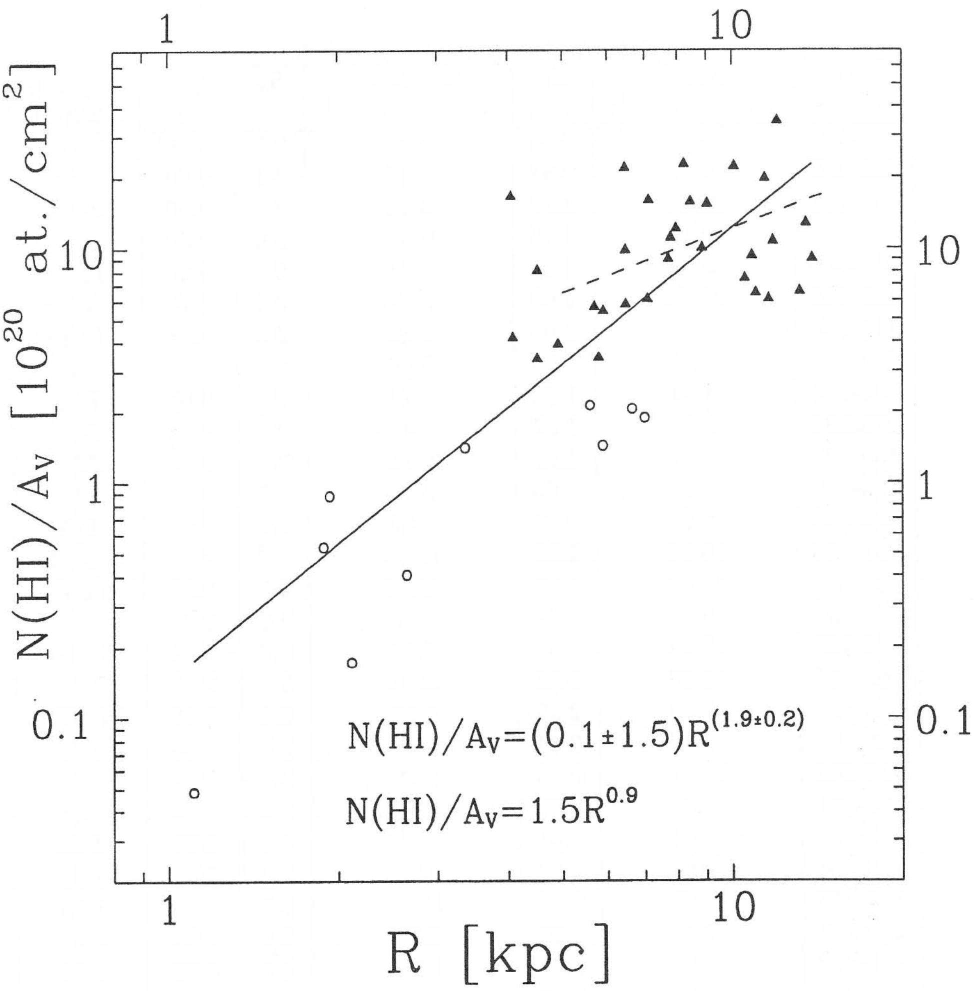

Fig. 9: Radial distribution of the atomic gas-to-dust ratio as derived for 33 (triangles) and 10 (open circles) globulars. The dashed line represents the gradient as determined by Braun & Walterbos (1999) for 6 HII regions in M31. The solid line represents a power law fit, indicating possible central hypermetallicity.

Table 1: Gas-to-dust ratios in M31

ID number	N(HI) (10^{20} at cm^{-2})	A_V *mag*	N(HI)/A_V at cm^{-2} mag^{-1}	R_V	log(*t*) t, yr	R [kpc], 0.2 kpc/′
063-124	16.86	2.55	6.61	2.5	8.48	13.21
206-257	5.21	0.64	8.15	3.1	9.60	4.52
039-101	13.97	2.27	6.16	2.3	9.90	11.65
094-156	14.91	1.48	10.08	2.9	9.00	8.85
017-070	14.49	1.59	9.11	2.9	9.30	13.88
185-235	26.32	1.66	15.86	2.4	8.78	8.45
116-178	28.07	3.00	9.36	2.3	7.78	10.86
068-130	10.17	1.79	5.69	4.1	9.60	5.70
204-254	9.70	1.58	6.14	2.8	9.00	7.09
073-134	5.77	1.67	3.46	2.3	8.48	5.80
135-192	9.74	1.07	9.11	3.2	9.70	7.71
153-000	5.65	1.65	3.43	2.9	8.85	4.51
096-158	10.00	2.37	4.22	2.9	8.70	4.08
061-122	15.69	1.22	12.86	3.7	9.85	13.54
180-231	31.88	1.60	19.92	2.8	9.00	11.43
235-297	36.14	1.03	35.09	2.9	8.30	12.50
044-107	17.59	2.34	7.52	2.0	7.84	10.54
161-215	13.36	0.83	16.10	3.1	9.30	7.12
038-098	15.59	2.39	6.52	2.4	7.48	11.03
093-155	13.34	2.44	5.47	2.6	7.85	5.91
217-269	19.72	0.86	22.93	3.4	9.30	8.22
228-281	5.77	0.99	5.83	3.3	9.30	6.48
117-176	36.04	1.61	22.39	3.1	8.60	10.09
213-264	4.03	1.02	3.95	2.2	9.30	4.91
165-218	23.03	2.06	11.18	2.6	7.48	7.79
209-261	12.38	1.25	9.91	2.6	9.00	6.47
211-262	28.06	1.81	15.50	2.6	7.78	9.04
229-282	5.98	0.27	22.16	2.7	8.30	6.46
239-000	28.15	2.60	10.83	2.2	7.00	11.83
178-229	5.70	0.34	16.76	3.5	10.04	4.06
174-226	16.09	1.32	12.19	2.9	9.60	7.96

result obtained by Braun and Walterbros (1992) for galactocentric gas-to-dust ratio gradient. Moreover, our result is consistent with Braun's - the 6 points they use for compare well with ours. Comparing the lines in Fig. 9 (the dashed line is from Braun and Walterbros 1992) one can see that the slope of our line is greater. This can be explained considering the fact that in our sample we also have clusters close to the centre, which may imply higher metallicity of the inner parts of the dust component of the disk. Table 2 summarizes what we determined for the clusters of our sample in terms of gas-to-dust ratios, ages, R_V.

Finally, we made a histogram of $N(HI)/A_V$ and compared it with those of other authors (Fig. 8). It is assuring that our $N(HI)/A_V$ distribution contains reasonable values for the Milky Way. The fact that we observe a peak at slightly lower values N(HI)/Av $\sim 9 \times 10^{20}$ atoms cm^{-2} mag^{-1} was already discussed but the distribution pattern we see suggests that our clusters are located in sampling varying with distance $N(HI)/A_V$. We compare our results for M31 gas-to-dust with the values for the Milky Way - data from Bohlin *et al.* (1978) and another estimate for M31, obtained by Lequeux (2000). Our value for the gas-to-dust ratio is probably less from that Lequeux gives because of the different technique used in determining $N(HI)/A_V$. He uses primarily UV data and having in mind the probable dust properties in terms of composition and size, it is completely understandable why Lequeux (2000) obtains three times larger gas-to-dust ratio then we do.

5. Conclusions

This work addresses several different problems. First, we determined the absorption in M31 disk at different radii. This was achieved by obtaining extinctions and appropriate values of the free parameter R_V for all 41 M31 clusters we study. Second, by comparing our extinction law with the average extinction law given by Cardelli *et al.* (1989), we estimated the ages of the clusters. At this point we found several candidates for young clusters but we don't assert it since we think that our method might not be very sensitive to the age. And finally, using column densities of HI (Brinks & Shane, 1984) we obtained a gas-to-dust ratios for M31, close to that in the Milky Way. We derive power law dependence of N(HI)/Av at the distance to the centre much steeper than those previously found (Braun & Walterbos, 1992; Nedialkov *et al.*, 2000) which may reflect the supersolar metallicity near the M 31 centre. Recently, Davidge (2001) suggested that the brightest stars in the bulges of M 31 and the Milky Way belong to an old, metal-rich population and they are bright not because of small age, but because of high metallicity. In the near future we intend to test a richer sample of globulars in M 31 because the number of clusters with known metallicities is already above 200 (Perrett *et al.*, 2000).

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