Dust properties of nearby disks: M 31 case

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Abstract. Several properties of the M 31 disk, namely: opacity, extinction law and gas-to-dust ratio are studied by means of optical and near-infrared photometry of ten globular clusters and galaxies seen through the disk. The individual extinctions of these objects were estimated with respect to several sets of theoretical spectral energy distributions for globulars and galaxies. Seven targets are consistent with reddened globulars, two - with starburst galaxies and one - with an elliptical. The extinction estimates agree with semi-transparent disk ($τ_V < 1$) in the inter-arm regions. The total-to-selective extinction ratio in those regions $2.75\pm 0.1$ is lower on average than the typical Galactic value of $R_V=3.1$. We also obtained a gas-to-dust ratio, similar to that in the the Milky way. It shows no correlation with the distance from the M31 center.

Keywords. galaxies: ISM, photometry, dust, extinction; globular clusters

1. Introduction

The dust in galaxies attenuates the light of background extragalactic sources. Recent studies (Holwerda et al. 2005) of morphologically representative samples of spirals shows that dust opacity of a disk arises from two distinct components: (i) optically thicker ($τ_V = 0.8 \div 8$) and radially dependent component, associated with the spiral arms, and (ii) relatively more constant optically thinner disk ($τ_V \sim 1$), dominating the inter-arm regions and the outskirts of the disk.

The nearby giant spiral galaxy M 31 is well suited for comprehensive studies of the interplay between the stars and the ISM. The radial distribution of the opacity in M 31 spiral arms, based on individual estimates towards OB stars, shows that the opacity exponentially decreases away from the bulge (Nedilakov & Ivanov 1998). However, a study of 41 globular clusters in M 31 indicates the absence of radial extinction gradient with the galactocentric distance (Savcheva & Tassev 2002).

Measuring the color excesses of objects behind the disks is an alternative method to constrain the disk opacity. It was applied to M 31 by Cuillandre et al. (2001) who used background galaxies. They concluded that the M31 disk is semi-transparent for distances larger than $R_{25}$.

Here we complement this work, presenting opacity estimates for galactocentric distance...
smaller than \( R_{25} \), derived from the comparison of apparent colors of background globulars and ellipticals with models.

### 2. Observations and data reduction

Our sample includes 21 background galaxy candidates located well within the standard M31 radius \( R_{25} \). They were selected from a number of heterogeneous sources: visual inspection of DSS and the NOAO archive photographic plates, dropouts from M31 globular cluster searches (Battistini et al. 1980). Our original intention was to base the study on background ellipticals only but five of our targets were recently identified as globulars, and their \([Fe/H]\) and \(v_r\) became readily available from Galleti et al. (2006).

We obtained \( HK\) imaging in Dec 1996 and Jan 1997 with ARNICA (Lisi et al. 1993) at 1.8m Vatican Advanced Technology Telescope on Mt. Graham. The instrument is equipped with a NICMOS3 (256 × 256 pixels) detector array, with scale of 0.505 arcsec/pixel. The data reduction includes the typical steps for infrared imaging: “sky” removal, flat-fielding, alignment and combination of individual images, separately for every filter and field. Ten of the targets (Table 1, Fig. 1) were identified on the \( UBVRI \) images from the Local Group Survey (Massey et al. 2006), obtained with the KPNO Mosaic Camera at 4m Mayall telescope.

#### Table 1. Sub-set of our original target list, with \( UBVRIHK \) photometry.

| No. | 2MASSX/2MASS name | Other name | Object\(^1\) | \(v_r\) [km s\(^{-1}\)] | \([Fe/H]\) | \(r_{gc}\) [arcmin] | \(N(\text{HI}+2\text{H}_2)\)\(^2\) \([\times10^{20} \text{at. cm}^{-2}]\) |
|-----|-------------------|------------|-------------|----------------|---------|----------------|------------------|
| 1.  | 2MASX J00451437+4157405 | Bol 370 | 1 | -347 | -1.80 | 52.2 | 1.895 |
| 2.  | 2MASX J00444399+4207298 | Bol 250D | 1 | -442 | - | 84.2 | 9.028 |
| 3.  | 2MASS J00420658+4118062 | Bol 43D | 1 | -344 | -1.35 | 30.8 | 12.836 |
| 4.  | 2MASS J00413428+4101059 | Bol 25D | 1 | -479 | - | 20.8 | 0.668 |
| 5.  | 2MASS J00413436+4100497 | Bol 26D | 1 | -465 | -1.15 | 20.8 | 2.170 |
| 6.  | 2MASS J00431491+4100182 | Bol 251 | 2 | - | - | 20.6 | 1.350 |
| 7.  | 2MASS J00430737+4127329 | Bol 269 | 2 | - | - | 19.6 | 12.384 |
| 8.  | 2MASS J00421236+4119008 | Bol 80 | 2 | - | - | 29.3 | 15.248 |
| 9.  | 2MASS J00413428+4101059 | Bol 25D | 2 | - | - | 79.1 | 16.120 |
| 10. | 2MASS J00425875+4108527 | Bol 140 | 3 | -413 | -0.88 | 31.7 | 6.654 |

**Notes:**

1. Following Galleti et al. (2006): 1 - confirmed globular clusters (GC), 2 - GC candidates, 3 - uncertain objects
2. Total hydrogen column density based on pencil beam estimates of CO(1\(\rightarrow\)0) intensity (Nieten et al. 2006), converted to molecular hydrogen column density using a constant \(X_{CO}\) conversion factor (Strong & Mattox 1996) and \(\lambda 21\) cm emission from the Westerbork map (Brinks & Shane 1984).

Clouds were present during most of the observations, forcing us to use the 2MASS Point Source Catalog (Cutri et al. 1993) stars for the photometric calibration (typically using 4–10 common stars per field). No color dependence was found, and the r.m.s. of the derived zero-points was \(\sim 0.05\) mag for both bands. The typical seeing of the optical images \((\sim 1.0''\) matches well that of the near-infrared data set \((\sim 1.5''\) ), allowing us to perform simple aperture photometry with 4'' radius. We used the standard IRAF\(^\dagger\) tasks. The zero points of the optical data are based on stars in common with the catalog of

\(\dagger\) IRAF is the Image Analysis and Reduction Facility made available to the astronomical community by the National Optical Astronomy Observatories, which are operated by AURA, Inc., under contract with the U.S. National Science Foundation.
Massey et al. (2006). The $V$-band magnitudes and the observed colors together with their errors are listed in Table 2. The majority of the infrared colors shows excellent agreement with the available 2MASS colors (see Fig. 2).

Table 2. $UBVRIHKL$ photometry of the objects listed in Table 1 Photometric systems: $UBV$ - Johnson, $RI$ - Cousins, $HK$ - Bessell & Brett (1988). The uncertainties include both the zero-point errors and the statistical errors of the individual measurements.

| No. | $V$    | $\sigma_V$ | $U - K$ | $\sigma_{U-K}$ | $U - I$ | $\sigma_{U-I}$ | $U - R$ | $\sigma_{U-R}$ | $B - K$ | $\sigma_{B-K}$ | $V - K$ | $\sigma_{V-K}$ | $U - H$ | $\sigma_{U-H}$ |
|-----|--------|------------|---------|----------------|--------|----------------|---------|----------------|--------|----------------|--------|----------------|--------|---------------|
| 1   | 16.18  | 0.08       | 3.85    | 0.30           | 2.23   | 0.31           | 1.84    | 0.32           | 3.02   | 0.23           | 2.53   | 0.10           | 3.67   | 0.30          |
| 2   | 17.60  | 0.02       | 6.19    | 0.09           | 3.51   | 0.06           | 2.69    | 0.06           | 5.11   | 0.09           | 4.25   | 0.08           | 5.65   | 0.06          |
| 3   | 17.15  | 0.02       | 6.46    | 0.05           | 3.90   | 0.06           | 3.08    | 0.05           | 5.16   | 0.07           | 4.21   | 0.05           | 6.13   | 0.06          |
| 4   | 18.23  | 0.03       | 6.25    | 0.07           | 3.49   | 0.10           | 2.80    | 0.05           | 5.34   | 0.10           | 4.19   | 0.06           | 5.74   | 0.07          |
| 5   | 18.23  | 0.03       | 5.72    | 0.07           | 3.43   | 0.10           | 2.70    | 0.05           | 4.85   | 0.10           | 3.81   | 0.07           | 5.39   | 0.07          |
| 6   | 17.77  | 0.03       | 5.82    | 0.07           | 3.46   | 0.10           | 2.79    | 0.04           | 4.65   | 0.09           | 3.69   | 0.06           | 5.35   | 0.06          |
| 7   | 18.49  | 0.03       | 5.83    | 0.09           | 3.51   | 0.07           | 2.96    | 0.06           | 4.68   | 0.11           | 3.72   | 0.09           | 5.31   | 0.09          |
| 8   | 17.14  | 0.02       | 5.10    | 0.06           | 3.28   | 0.06           | 2.59    | 0.04           | 3.98   | 0.08           | 3.23   | 0.05           | 5.01   | 0.06          |
| 9   | 18.26  | 0.02       | 6.36    | 0.07           | 3.76   | 0.07           | 2.95    | 0.06           | 5.20   | 0.08           | 4.27   | 0.04           | 5.90   | 0.08          |
| 10  | 17.37  | 0.02       | 4.64    | 0.07           | 2.38   | 0.12           | 2.19    | 0.04           | 3.59   | 0.09           | 3.08   | 0.07           | 4.43   | 0.07          |

3. Dust properties of M 31 disk from $\chi^2$-test minimization

The intrinsic near-infrared colors of ellipticals are nearly identical: $(H-K)_0 \sim 0.22$ mag, as demonstrated by Persson et al. (1979). Assuming all the targets belong to that Hubble
Figure 2. Comparison between the colors derived in this work and the available 2MASS colors. Note that the photometry of Bol269 (target No. 7 in our list) was flagged as suspect in the 2MASS Point Source Catalog.

type, the opacity of the disk that lay between them and the observer can easily be calculated, taking into account the internal Milky Way extinction, i.e. from the work of Schlegel et al. (1998). However, the evident contamination of the sample by globular clusters requires also to consider for each object the possibility that it is a M31 globular, with the typical globular cluster colors. Furthermore, a cluster may be located in front of the M31 disk, adding extra degree of complication to the analysis.

To address these issues we developed a multicolor \( \chi^2 \) minimization technique to derive simultaneously the disk opacity and number of other parameters: gas-to-dust ratio, extinction law and last but not least – the nature of the object (elliptical galaxy or globular cluster). It allows also to fix some of these parameters, while still varying the rest of them. The intrinsic colors of globulars were adopted from the model of Kurth et al. (1999) and for the ellipticals – from Bicker et al. (2004).

The results from the test are presented in Table 3. The free parameters in the case of globular clusters (left side of the Table 3) are: age, abundance \( Z \), \( R_V \), and in the case of the elliptical galaxy models (right side of the Table 3) they are: redshift \( z \), \( R_V \), and \( A_V \). We created a multi-dimensional grid, with steps of 0.01 along all axes and calculated the \( \chi^2 \) for every grid node.

The preliminary tests reveal that in all cases \( BI \)-bands dominate the values of \( \chi^2_{\text{min}} \). These bands have the largest systematics with respect to external photometry (Massey et al. 2006). To account for that and to minimize their impact we tentatively added 0.20 mag to the \( B \)-band and 0.12 mag to the I-band magnitude errors. The errors listed in Table 2 do not reflect this modification. As a result, we have relatively more equal contribution of the different colors to the \( \chi^2_{\text{min}} \).

The globular cluster model fits much better the colors of most targets than the elliptical model. The typical opacity \( \tau_V \) across the M31 disk is \( \sim 1 \) mag. There are two exceptions (objects No. 8 and No. 10) for which neither model yields a reasonable match.

Interestingly, \( R_V \) in M31 is lower than the typical Galactic value of 3.1, and it is similar to the one obtained by Savcheva & Tassev (2002). This may indicate a smaller mean size of the dust grains in the diffuse component of M31 ISM, in comparison with the Milky way. Although the targets are located well within standard radius \( R_{25} \), where the active star formation still takes place, all of them are projected in the inter-arm regions where the opacity of the disk stays relatively low, as seen from the column density values in Table 1. Here we assumed the Galactic gas-to-dust ratio (Bohlin et al., 1978).

The relation between total gas column densities and the derived extinctions, corresponding to \( R_V = 3.1 \) and \( \chi^2_{\text{min}} \), is plotted in Fig 3. Surprisingly, the derived extinctions
Table 3. Summary of the $\chi^2$ minimization. The matches of the apparent colors to the globular cluster models of Kurth et al. (1999) is given in the left and to the intrinsic colors of ellipticals predicted by the GALEV models of Bicker et al. (2004) is given on the right. The numbers of the targets as the same as in Table 1. The table also reports if the $A_V$ corresponding to the minimum $\chi^2$ agrees (within the errors) with the total gas density derived from the combined $HI$ map of Brinks & Shane (1984) and the CO(1→0) map of Nieten et al. (2006). The asterisk indicates a fixed parameter.

| No. | Globular Cluster Model Fit Parameters | Elliptical Galaxy Model Fit Parameters | Derived Type |
|-----|-------------------------------------|--------------------------------------|--------------|
|     | Age [yr]  | Abundance $Z$  | $R_V$ | $A_V$ | $\chi^2_{min}$ | $\delta$ vs. gas? | Redshift $z$ | $R_V$ | $A_V$ | $\chi^2_{min}$ | $\delta$ vs. gas? |
| 1.  | 0.9 x 10^5 | 0.0001 | 3.10* | 1.81 | 1.288 | no | 0.000 | 3.10* | 0.00 | 39.950 | no |
|     | 0.9 x 10^5 | 0.0003* | 3.10* | 1.46 | 2.510 | no | 0.000 | 6.00 | 0.00 | 39.950 | no |
|     | 0.6 x 10^5 | 0.0003* | 2.43 | 1.45 | 1.534 | no | 0.000 | 3.10* | 0.00 | 39.950 | no |
| 2.  | 0.4 x 10^5 | 0.0500 | 3.10* | 2.41 | 2.400 | no | 0.075 | 3.10* | 0.98 | 7.562 | yes |
|     | 0.4 x 10^5 | 0.0500 | 3.10* | 2.41 | 2.400 | no | 0.075 | 3.42 | 1.05 | 6.900 | yes |
| 3.  | 0.8 x 10^5 | 0.0050 | 3.10* | 0.50 | 3.406 | yes | 0.026 | 3.10* | 1.41 | 45.111 | yes |
|     | 3.0 x 10^5 | 0.0009* | 3.10* | 2.60 | 19.558 | no | 0.021 | 2.15 | 1.18 | 10.404 | yes |
|     | 2.0 x 10^5 | 0.0009* | 2.77 | 2.54 | 8.552 | no | 0.021 | 2.15 | 1.18 | 10.404 | yes |
| 4.  | 3.0 x 10^5 | 0.0500 | 3.10* | 0.86 | 2.152 | no | 0.072 | 3.10* | 1.06 | 7.180 | no |
|     | 3.0 x 10^5 | 0.0500 | 3.10* | 0.86 | 2.152 | no | 0.072 | 2.75 | 0.97 | 5.692 | no |
| 5.  | 8.0 x 10^5 | 0.0400 | 3.10* | 0.21 | 0.870 | no | 0.004 | 3.10* | 0.86 | 24.117 | no |
|     | 1.1 x 10^5 | 0.0014* | 3.10* | 1.73 | 7.522 | no | 0.004 | 1.77 | 0.62 | 3.649 | no |
|     | 2.0 x 10^5 | 0.0014* | 2.75 | 2.00 | 2.786 | no | 0.004 | 1.77 | 0.62 | 3.649 | no |
| 6.  | 1.4 x 10^5 | 0.0400 | 3.10* | 0.01 | 1.707 | no | 0.061 | 3.10* | 0.83 | 69.838 | no |
|     | 1.4 x 10^5 | 0.0400 | 3.10* | 0.01 | 1.707 | no | 0.061 | 1.08 | 0.40 | 8.572 | no |
| 7.  | 1.4 x 10^5 | 0.0450 | 3.10* | 0.00 | 5.913 | no | 0.064 | 3.10* | 0.84 | 61.223 | yes |
|     | 1.4 x 10^5 | 0.0450 | 3.10* | 0.00 | 5.913 | no | 0.064 | 1.00 | 0.40 | 13.223 | yes |
| 8.  | 1.3 x 10^5 | 0.0200 | 3.10* | 0.00 | 34.012 | no | 0.024 | 3.10* | 0.56 | 137.883 | yes |
|     | 1.3 x 10^5 | 0.0200 | 3.10* | 0.00 | 34.012 | no | 0.024 | 1.00 | 0.33 | 27.456 | yes |
| 9.  | 3.0 x 10^5 | 0.0500 | 3.10* | 0.97 | 4.321 | yes | 0.042 | 3.10* | 1.26 | 12.802 | yes |
|     | 2.0 x 10^5 | 0.0005* | 3.10* | 2.67 | 7.154 | no | 0.061 | 2.63 | 1.11 | 9.039 | yes |
|     | 2.0 x 10^5 | 0.0005* | 3.10* | 2.67 | 7.154 | no | 0.061 | 2.63 | 1.11 | 9.039 | yes |
| 10. | 1.0 x 10^5 | 0.0500 | 3.10* | 0.50 | 13.716 | yes | 0.042 | 3.10* | 0.15 | 54.800 | yes |
|     | 0.9 x 10^5 | 0.0025* | 3.10* | 2.25 | 26.747 | yes | 0.042 | 1.00 | 0.15 | 30.674 | yes |
|     | 0.9 x 10^5 | 0.0025* | 2.69 | 2.06 | 17.238 | no | 0.042 | 1.00 | 0.15 | 30.674 | yes |

of the candidate globulars (targets No. 6 and 9) correlate better with the gas density if we use intrinsic colors derived from the elliptical models. We contribute this to the spatial variations of the reddening law.

Our analysis also considers the K-correction. We used the HyperZ code of Bolzonella et al. (2000), that includes a variety of spectral energy distributions for different morphological types of galaxies. The results are presented in Table 4. Both cases – fixed to the elliptical type and free morphological types yield reasonable $\chi^2_{min}$ values. The extinction estimates are lower and the redshifts are higher than those derived earlier, indicating a degeneracy between these two quantities. The metallicity-opacity degeneracy is apparent in Table 3 as well: the higher is the abundance $Z$, the lower is the derived extinction and vice versa. The HyperZ tends to classify our targets as starburst galaxies, explaining the larger extinction values in comparison with the case of fixed elliptical morphological type. Note that a large fraction of the extinction may be internal to a starburst galaxy.
Figure 3. The agreement between the total hydrogen column density $N(H)$ and the color excess $E_{B-V}$ with respect to Kurth et al. (1999) model colors of globulars (left) and with respect to colors of ellipticals (right) as predicted by the GALEV models (Bicker et al. 2004). The extinction values are listed in Table 2 and correspond to $R_V=3.1$ and $\chi^2_{\text{min}}$. Dashed lines represent the expected range and the thick line is the mean Galactic gas-to-dust ratio (Bohlin et al. 1978).

and not related to the M 31 disk. This might be the case for targets No. 8 and 10 which, together with No. 9 are our best candidates for galaxies, laying behind the M 31 disk.

4. Conclusions

We measure the opacity of the M 31 disk from the color excesses of 21 objects – a mixture of galaxies behind the disk and globular clusters. Seven of them are consistent with globulars, two - with starburst galaxies and one - with an elliptical galaxy. Their extinction estimates are consistent with a semi-transparent disk ($\tau_V \lesssim 1$) in the inter-arm regions. We confirm the conclusion of Savcheva & Tassev (2002) that the total-to-selective extinction value $R_V$ in the diffuse ISM of M 31 is on average lower than the typical Galactic value of $R_V=3.1$. The gas-to-dust ratio appears similar to that in the Milky way and it is independent from the galactocentric distance, which might indicate Solar abundances along the line of sight studied here (within $20'\div85'$ from the M 31 center).

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Table 4. Summary of the $\chi^2$ minimization considering the K-corrections, for two different redshifts. The “intrinsic” redshifted colors of the galaxies were determined with the HyperZ (Bolzonella et al. 2000). The numbers of the targets as the same as in Table 1. The grid resolution is 0.05 along all axes and the Galactic extinction law of Allen (1976) is assumed. The rest of the columns are identical with those in Table 3.

| No. | Redshift $z$ | $A_V$ [mag] | $\chi^2_{min}$ | dust vs. gas? | Galaxy Type | Redshift $z$ | $A_V$ [mag] | $\chi^2_{min}$ | dust vs. gas? | Galaxy Type |
|-----|-------------|-------------|----------------|--------------|-------------|-------------|-------------|----------------|--------------|-------------|
| 1.  | 0.130       | 0.05        | 4.562          | yes          | elliptical* | 0.135       | 0.05        | 0.673          | yes          | starburst   |
| 2.  | 0.200       | 0.55        | 1.743          | yes          | elliptical* | 0.200       | 0.55        | 1.743          | yes          | elliptical  |
| 3.  | 0.145       | 0.70        | 1.109          | yes          | elliptical* | 0.140       | 1.00        | 1.625          | yes          | starburst   |
| 4.  | 0.200       | 0.35        | 1.482          | no:          | elliptical* | 0.150       | 1.45        | 1.365          | no           | starburst   |
| 5.  | 0.150       | 0.25        | 0.546          | yes          | elliptical* | 0.150       | 0.75        | 0.464          | no           | starburst   |
| 6.  | 0.145       | 0.15        | 2.700          | yes          | elliptical* | 0.155       | 0.05        | 1.807          | yes          | starburst   |
| 7.  | 0.145       | 0.15        | 3.926          | no:          | elliptical* | 0.350       | 0.10        | 1.051          | no           | starburst   |
| 8.  | 0.110       | 0.10        | 2.417          | no           | elliptical* | 0.105       | 0.95        | 2.230          | yes          | starburst   |
| 9.  | 0.155       | 0.75        | 1.246          | yes          | elliptical* | 0.155       | 0.75        | 1.246          | yes          | elliptical  |
| 10. | 0.050       | 0.00        | 4.659          | no           | elliptical* | 0.150       | 0.50        | 2.571          | yes          | starburst   |

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