Astron. Astrophys. 325, 144–148 (1997)

ASTRONOMY AND ASTROPHYSICS

A simple effective method to estimate the galactic extinction towards galaxies in the plane of the Milky Way

M. Gajdošík[1,2] **and R. Weinberger**[1]

[1] Institut für Astronomie der Leopold-Franzens-Universität Innsbruck, Technikerstraße 25, A-6020 Innsbruck, Austria (http://astro.uibk.ac.at)
[2] Department of Astronomy and Astrophysics, Faculty for Mathematics and Physics, Comenius University, Mlynská Dolina, 842 15 Bratislava, Slovak Republic (gajdosik@center.fmph.uniba.sk)

Received 22 August 1996 / Accepted 23 January 1997

Abstract. Elliptical galaxies and bulges of spiral galaxies have quite similar, well-defined optical colours. It is just these bulges that are left if a (spiral) galaxy suffers from a considerable foreground extinction as is the case for many of the thousands of galaxies that have been detected in recent years in the "zone-of-avoidance" of the Milky Way. By use of the "old" Palomar Sky Survey (whose red-sensitive and blue-sensitive exposures had consecutively been taken for each field), measuring the red and blue bulge profiles there, led to astonishingly accurate results for their galactic, i.e. foreground extinction. With this quick and simple method it will be possible in future to determine the total galactic extinction along many lines-of-sight in the Galaxy, to supplement data on the spatial distribution of the interstellar extinction with a maximum value and, eventually, to develop a dust-model of the Milky Way. We detected a pronounced dependence of the 100 μm *vs* A_V or 60μm *vs* A_V ratio on the galactic longitude.

Key words: methods: observational – (ISM:) dust, extinction – Galaxy: structure – galaxies: fundamental parameters

1. Introduction

The question of how much light is obscured from our sight by intervening dust is a significant one which impinges on many areas of astrophysics. It is estimated that about nine/tenths of the Milky Way are invisible at optical wavelengths due to this component of the interstellar matter. Quite recently, not only the Milky Way is the focal point of discussion in this respect, but there are also remarkable efforts to understand the observational effects of dust in other galaxies (see, e.g., the proceedings of the meeting on "The Opacity of Spiral Disks", Davies & Burstein 1995).

Particularly, the spatial distribution of the interstellar extinction is of significance in many respects and can be investigated in great detail in our Galaxy only. A pioneering work has been undertaken by Neckel (1967) and Neckel & Klare (1980), who had computed extinction values and distances from UBV, MK (Morgan Keenan) and Hβ data for many thousand stars. With this method, however, the Galaxy cannot be penetrated, i.e. the extinction-distance diagrams are limited in distance, of course. The use of extragalactic systems - beyond the dust layer in the Milky Way's plane - would, in principle, yield total extinctions.

In the most recent years, $> 10^4$ galaxies have been optically identified in the zone-of-avoidance (ZOA), dubbed so because of the apparent lack of galaxies as found by Hubble (1934). Such searches for extragalactic sources behind the Milky Way are of interest for several research fields. In the northern galactic plane, 5000 galaxies have been identified by a group of astronomers from Innsbruck (see, e.g., Seeberger et al. 1994). Hundreds of these galaxies will be suitable for measurements with our method which does not require any telescope time, but makes use of the Palomar Observatory Sky Survey (POSS) prints or plates.

2. Material and method

2.1. Colours of galaxies

As Cameron (1990) has pointed out, there is a significant reduction of the diameter of galaxies at foreground extinctions larger than about one magnitude in the visual; a spiral galaxy would then quickly "loose" its outer regions and the bulge is left over. This finding is important for our method which is based on (optical) measurements of galaxies beyond the plane of the Milky Way, i.e. objects which suffer from often considerable galactic extinction.

Short: obscured spiral galaxies will look more or less like ellipticals and since bulges of spirals and elliptical galaxies have practically the same true (unreddened) colours, they can be treated in the same way. There are a couple of papers that show that the same colours prevail and how well-defined they are. Pioneering measurements in this respect were presented by de Vaucouleurs (1976) who determined for both spiral's bulges and

Send offprint requests to: M. Gajdošík ellipticals $(B-V)_0$ = +0.9 ± 0.1 and $(U-B)_0$ = +0.45 ± 0.15. For E and S0 galaxies an extensive VRI aperture photometry in the Cousins system was reviewed by Buta (1995), leading to $(V-R)_0 \approx$ +0.55 and $(V-I)_0 \approx +1.20$ (his Fig. 3). With these data and the above-given colours of de Vaucouleurs, intrinsic "true" colours for the POSS passbands could be calculated.

2.2. POSS I, the most suitable material

The use of the so-called "old" POSS, nowadays often cited as POSS I, may appear obsolete. Why not use the new POSS II with its better resolution (due to fine-grain emulsion) and fainter limiting magnitude? There are two main reasons for our choice (besides the fact that the POSS II has not been fully delivered yet):

- The red-sensitive (E) and blue-sensitive (O) plates of each field were taken in a consecutive way; since the longest E-exposures were not exposed for more than 1 hour, the blue ones for a maximum of 15 min, and the plate changes were carried out within a few minutes, a field was completely finished after 1.5 hours at most. Both the seeing and the transparency of the atmosphere did hardly change within this period. These facts, i.e. stable conditions, are crucial for our measurements of galaxies. The POSS II red and blue exposures, however, were *not* taken consecutively; sometimes, several years passed between the exposures for the same field.
- A comparison of diameter profiles for galaxies to estimate the extinction in the red and the blue requires an optical wavelength span as large as possible, of course. The effective wavelength range between blue and red is 2350 Å for POSS I (blue:≈ 4100 Å; red: ≈ 6450 Å), but only 1650 Å for POSS II (blue: ≈ 4800 Å; red: same as above).

No question that the POSS I plates are equally well or even better suitable than the prints for the measurements described below; we had, however, only the POSS I prints at our disposal, like most astronomical institutes.

2.3. Measurements on POSS I

The method is based on the comparison of the image of a galaxy in the ZOA on the red (R) and the blue (B) POSS prints. We started by scanning the object on both R and B prints and chose an enlargement of 6.5× on the microscope. The prints were illuminated from above with an electric ring bulb from a distance which allowed a not too intense, but seemingly uniform illumination. Also, a "flat-field" was taken to correct for the possible non-uninformity of the illumination and for the camera response. The images were digitized with a software developed at our institute.

For comparison purposes of both images, first the coordinate systems had to be exactly adjusted to each other. Then they were flatfielded and subtracted from the median of the flatfielded images. The final images were created by smoothing the images with a radius of one pixel. Subsequently, for the bulge of the galaxy (in case of possible spirals) two cross-sections were defined. The criteria for these cross-sections were that i) they had to lead right through the core of the object, and ii) they had to avoid stars projected on the galaxy, if possible.

Mostly, we used two perpendicular cross-sections, but in some cases it was necessary to rotate the images to find a convenient section, i.e. undisturbed by stars. Subsequently, a Gaussian fitting was carried out, that is the galaxy (and surrounding stars) were fitted by a Gausssian function. A linear background was supposed.

The result of the procedure then was the ratio of the area of the Gaussian peaks in red and in blue, where a mean value of the two cross-sections in each colour was taken. In several cases there was a "halo" around the galaxy image (i.e. due to the dimly visible spiral arms or the brighter regions adjacent to the bulge of a galaxy) that had to be taken into account in the fit. Also, an appropriate length of the single scans had to be chosen to accurately adjust the background. The major difficulty are very closely projected stars. In these cases the method became ambiguous. Particularly galaxies with a diameter of a few arcminutes are endangered to be contaminated by foreground stars. We recommend not to measure galaxies with such a kind of strong "stellar contamination" with our method. In addition, in a few cases the profiles were saturated in the inner parts of a galaxy (for example in Maffei 1). In such cases our measuring error is enlarged due to an improper fit and we underestimate somewhat the red/blue (R/B) ratio, since a (reddened) galaxy is more saturated in the red.

For the calibration of the extinction values, i.e. for searching for a relation between the R/B ratio and extinction $A_{\rm V}$ along the line-of-sight to the galaxies, we made use of the few galaxies in the ZOA with a known extinction. In their paper on optically published galaxies within $|b| \leq 5°$, Weinberger et al. (1995) presented these galaxies (their table 2) and their $A_{\rm V}$ data. One could ask why not to use the "volume" of the galaxy image instead of the area. The reason is that the calibration becomes extremely steep, particularly for low R/B values and extinctions within the magnitude range of $0 \leq A_{\rm V} \leq 2$ mag could only hardly be distinguished. In the region covered by (and visible or usable on) the POSS I there were less than 10 such objects. It will be mandatory in future to enlarge this sample.

3. Results and discussion

3.1. The R/B vs $A_{\rm V}$ relation

Altogether 9 galaxies were found to have measurable R/B profiles *and* relatively accurate foreground extinction data. In Fig. 1 these objects are shown in an R/B *vs* $A_{\rm V}$ relation. The highest obscured galaxy is Maffei 1 (note that Maffei 2 is not visible on the blue-sensitive POSS I), whereas the galaxy with the lowest extinction (UGC 11344) was taken from a paper by Lu et al. (1992).

It is obvious that there is a surprisingly clear relation between the R/B values and the $A_{\rm V}$ data.

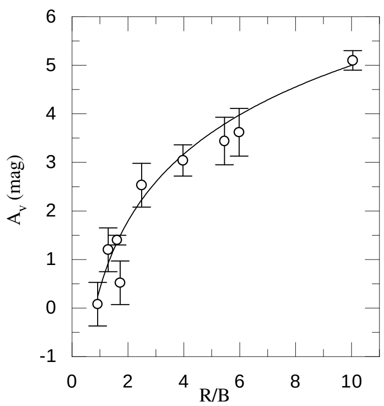

Fig. 1. The small sample of galaxies with a "bulge" or being of elliptical type in the zone-of-avoidance that have a well-determined ($\Delta A_V \leq \pm$ 0.5 mag, see Table 2 in Weinberger et.al. 1995) foreground extinction and which are measurable on the "old" Palomar Sky Survey exposures. The line represents a weighted best fit

Table 1. Measurements of close ($\leq 5'$) galaxy pairs to check the validity of our R/B method

No.	ZOAG name	R/B	s.d.	A_V	POSS	x,y (mm)	
1a	G 047.30+09.53	1.31		0.95	287	318.8	115.1
1b	G 047.35+09.46	1.32	0.02	0.98	287	314.2	116.0
2a	G 092.16−02.29	1.76		1.54	589	230.0	153.4
2b	G 092.18−02.29	1.71	0.09	1.48	589	228.9	153.8
3a	G 125.60−03.92	1.77		1.55	596	038.0	071.8
3b	G 125.60−03.91	1.73	0.05	1.50	596	038.0	072.1
4a	G 128.65−03.53	1.68		1.43	1240	184.7	069.9
4b	G 128.69−03.49	1.52	0.06	1.24	1240	182.8	071.8
5a	G 129.34+06.41	2.76		2.42	878	142.5	266.7
5b	G 129.41+06.39	2.00	0.16	1.78	878	138.8	264.4
6a	G 160.39+00.13	5.46		3.44	644	086.9	320.0
6b	G 160.45+00.08	3.97	0.20	3.04	644	086.9	315.5
7a	G 237.64+06.71	1.52		1.24	1010	211.1	172.3
7b	G 237.67+06.74	1.60	0.04	1.34	1010	208.8	172.7
8a	G 243.46+04.61	1.98		1.76	921	297.3	168.5
8b	G 243.49+04.53	2.25		2.01	921	299.7	164.5
8c	G 243.50+04.56	1.98	0.06	1.76	921	298.4	165.1

In the figure, a best fit is given. This empirical logarithmic curve

$$A_V = \mathrm{a} + \mathrm{b}\,\log\left(\frac{\mathrm{R}}{\mathrm{B}}\right) \quad (1)$$

is reasonable from a physical point of view, although data are missing to provide an unambiguous evidence.

The expected ratio of intensities of a galaxy in red and in blue is:

$$\frac{I_R}{I_B} = \mathrm{k}\,10^{-\frac{2}{5}(A_R - A_B)} \quad (2)$$

where A_R and A_B are the selective extinctions and the constant k reflects the intrinsic colour of the galaxy and the response of the detector in both bands. Assuming a standard extinction curve, the colour excess E_{B-R} is linearly related to the visual extinction:

$$A_B - A_R = \mathrm{c}\,A_V \quad (3)$$

where c $\approx$ 0.57 from the interstellar extinction law (Savage & Mathis 1979). To compare the values of the ratio R/B (ratio of the measured areas of the peaks) to the ratio of intensities, a photographic calibration of intensities would be necessary.

The least squares fit for the values on the ordinate of Fig. 1 are a = 0.41 ± 0.12 and b = 4.59 ± 0.25. The points were weighted according to the error of extinction, $g_i = 1/(\Delta A_V)^2$. It will be possible to weighten also according to the error of the R/B ratio as soon as we will have much more data.

3.2. The validity of the method

Although Fig. 1 looks convincing and is in accordance with what would theoretically be expected, we wanted to see whether the method and its outcome as evident in Fig. 1 are indeed reliable from a practical point of view. As a test to basically check the validity of the method, we chose a small sample of obscured (spiral or elliptical) galaxies that had to fulfil one important condition only: They had to be located at an angular distance of not more than $5'$ from each other. For such galaxy pairs (where it is of course insignificant whether they are true pairs or not) we can assume that the galactic foreground extinction is the same or almost the same; we further assumed that their intrinsic colours are the same too. Provided these assumptions hold, the differences in the derived A_V data should be maximum errors of the method itself.

We chose (mostly from catalogue data of the Innsbruck galaxy team) 7 such close pairs and 1 close triple and selected them to mostly be at widely different galactic longitudes. Short, we measured these galaxies with the method as described above and determined their foreground extinction by use of the relation shown in Fig. 1. In Table 1 we list some details on these galaxies and the results of the measurements.

In the second column we give the designation for the galaxies. ZOAG means Zone-Of-Avoidance-Galaxy and the next G shows that galactic coordinates are given. In column (3) we list the mean values of the R/B ratio for each galaxy. Next, assuming that the extinction is the same for both galaxies of a pair and that the intrinsic colours are the same, we calculated the standard deviation of all R/B values measured for the pair and related it to the mean R/B ratio. Thus, upper limits for relative standard deviations are listed in column (4). In the subsequent column there are the visual extinctions contained as derived from Fig. 1 (Eq. 1). For identification purposes the columns (6) and (7) give the number of the POSS print and the rectangular coordinates (in mm), measured from the lower left corner of the respective fields.

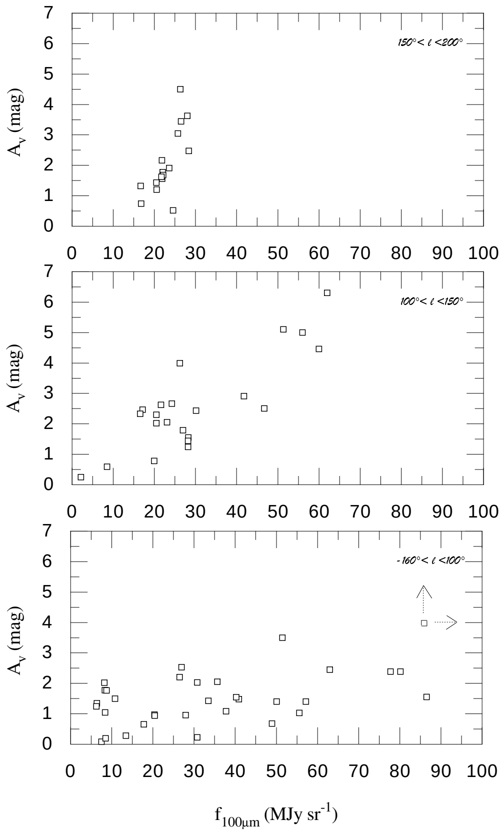

Fig. 2. The IRAS 100μm emission - an average over the emission of usually 4 positions that are mostly several arcmin away around a galaxy *vs* the visual extinction along the line-of-sight to a given galaxy. Each point in the diagram refers to one extragalactic object. The arrowed data point corresponds to a galaxy with a minimum $A_{\rm V} \approx 4^m$ and a $I_{100\mu}$ = 265.4 MJy sr^{-1} (Laustsen et. al. 1977). Note the strong dependence of the relation on galactic longitude.

The error of the visual extinction is caused both by the error of the R/B relation and by the uncertainty of the parameters a and b from the calibration:

$$\Delta A_{\rm V} = \sqrt{(\Delta a)^2 + \left(\Delta b \log \frac{R}{B}\right)^2 + \left(\frac{b}{\ln 10} \frac{\Delta \frac{\rm R}{\rm B}}{\frac{\rm R}{\rm B}}\right)^2} \qquad (4)$$

where Δa, Δb are the errors of the parameters of the fitting curve and $\frac{\Delta \frac{\rm R}{\rm B}}{\frac{\rm R}{\rm B}}$ is the mean relative error of the R/B ratio. Thus, the error of the visual extinction is (less than) 0.32 mag for 1 σ, a quite satisfying low value.

The mean relative standard deviation of the R/B ratio of the pairs is 8.5%. Excluding the pair no. 6 (plate 644), where there are measured (possibly different) values of extinction (Sandage 1975), this value is lowered to 6.9%.

3.3. A remarkable dependence of $A_{\rm V}$ on galactic longitude

A major application of our method will certainly be the attempt to relate $A_{\rm V}$ data to already existent data material at various wavelengths, and it is obvious to try to relate these extinction data to (galactic) infrared emission in the immediate (angular) vicinity of the galaxies. The outcome that one expects would be a diagram that could show a clear relation between the infrared fluxes of the interstellar (galactic) dust and $A_{\rm V}$. It would be somewhat analogous to the famous $N_{\rm H}/E_{\rm B-V}$ relation (Burstein & Heiles 1982).

As a preliminary attempt towards this goal - the presentation of copious data is however beyond the scope of this paper - we determined the galactic IRAS 60μm and 100μm emission around, but close to, 70 extragalactic objects with either known foreground extinction data or $A_{\rm V}$ values determined by our method. Almost all of them are galaxies, but e.g. a few globular clusters were included too. The results are very similar for the 60μm and the 100μm emission and clearly indicate that there is a pronounced dependence of this relation on the galactic longitude - see Fig. 2.

This dependence is noteworthy indeed. We intend to work out this behaviour in a subsequent paper on the basis of many more values in our figure and we will try to explain this find there. However, we anticipate the physical reason in this paper: the fact that the infrared emission per unit visual extinction is minimum in the direction of the anticenter and maximum in the solar circle suggests that the intensity of the interstellar radiation field is of main significance in this respect. Similar results were achieved by Boulanger and Pérault (1988), who found different values of the infrared emission per H atom in various parts of the Milky Way. Anyway, Fig. 2 clearly indicates that there is no Galaxy-wide relation at all between the FIR dust emission and the visual extinction.

4. Conclusions

We present a new simple optical method to estimate the foreground extinction of galaxies that are strongly reddened by dust in the Milky Way. Many thousand of such galaxies were discovered in most recent years. The material used are prints of the "old" Palomar Observatory Sky Survey where profiles have been derived of these obscured galaxies which often show nothing but their bulges (in case of spirals). A clear relation between the foreground $A_{\rm V}$ values and the red/blue profile ratio was found; the best fit is in accordance with what can be expected from a theoretical point of view. The application to close galaxy pairs (where an almost identical galactic foreground extinction can be assumed) showed the reliability of the method. An unexpected quite interesting outcome is the finding, that there is a pronounced dependence of the relation between $A_{\rm V}$ and the galactic IRAS 60μm or 100μm emission on galactic longitude. This means that there is no uniform relation of such a kind for the Galaxy, opening up a new powerful possibility for investigating the infrared emission - and the causes for it - in various parts of our Milky Way.

Acknowledgements. M.G. is grateful for a grant of the Austrian Bundesministerium f. Wissenschaft, Verkehr und Kunst. Both authors are grateful for various support and advice to their colleagues, particularly to Dr. Kimeswenger. Thanks are also due to Dr. Seeberger who pointed

out the possible potential of the type of investigations carried out by us.

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