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The Opacity of the Galactic Disk derived with Planetary Nebulae

J.Köppen[1,2,3] and J.-L.Vergely[1]

[1] *UMR 7550, Observatoire Astronomique, 11, rue de l'Université, F-67000 Strasbourg, France*
[2] *Institut für Theoretische Physik und Astrophysik der Universität, D-24098 Kiel, Germany*
[3] *International Space University, Parc d'Innovation, F-67400 Illkirch, France*

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ABSTRACT

Planetary nebulae of the Galactic bulge are used as background sources to probe the extinction in the disk. A systematic decrease of the extinctions with galactic latitude is found as well as a genuine scatter about the mean relation. Both are well accounted for by a model of small clouds randomly distributed in an exponential disk similar to the gas disk, with average cloud extinctions taken from the classical models derived from solar neighbourhood stars. The latter models thus provide also an excellent description for the global extinction of the disk. The pole-to-pole extinction of the Milky Way is found as $A_V = 1.4$, and in the plane one has $A_V = 27$ to the centre, in agreement with far-IR studies, but also with individual external galaxies. This indicates that our Galaxy is optically thin, a property shared with other spirals. Observable properties of galactic disks with our extinction model, as would be seen in external galaxies, are presented.

Key words: dust, extinction – Galaxy: structure – galaxies: ISM – galaxies: fundamental parameters – planetary nebulae: general

1 INTRODUCTION

What is the true luminosity of a spiral galaxy, i.e. its total visible mass? Such knowledge is e.g. the basis of the extragalactic distance scale via the Tully-Fisher-relation. One distinct feature of disk galaxies is the presence of dust in their disks, which is seen as dark lanes along the spiral arms and in edge-on galaxies as the strong obscuration by a thin disk in the galactic plane. Thus a proper correction for the effects of dust extinction is required.

How large is the optical depth of disk galaxies? Holmberg's (1975) statistical study from the dependence of the observed surface brightness of galaxies on inclination angle seemed to suggest that the interstellar medium in external galaxies is optically thin in the vertical direction. Disney et al. (1989) emphasized that the behaviour found by Holmberg cannot be interpreted as unambigous evidence for an optically thin dust disk, because it is strongly influenced by the spatial distribution of stars and dust. Subsequent statistical studies of the properties of galaxies have not been able to resolve this question, as summarized by Jones et al. (1996).

What can be said from direct measurements of the extinction? From infrared observations in several edge-on galaxies one finds maximum extinctions of about $A_V = 2$ in the dust lane (Wainscoat et al. 1989, Aoki et al. 1991, Knapen et al. 1991, Jansen et al. 1994); these directly measured values, however, do not take into account a realistic distribution of stars and dust in an (exponential) disk. Doing this, Kylafis and Bahcall (1987) derive a visual optical thickness of the whole disk, in the plane, for NGC 891 of 10, which converts into a vertical optical thickness of 0.46. In the Milky Way, the extinction in the plane upto the centre is found to be $A_K \approx 3$ (Rieke & Lebofsky 1985). With COBE, whose 1.25μ image nicely shows the thin strip of obscuration in front of the bulge (Weiland et al. 1994), Arendt et al. (1994) deduce $A_{1.25\mu} \approx 4$ which gives $A_V \approx 30$. Also, the far-IR emission from grains can be used to infer on the dust distribution (Sodroski et al. 1997, Davies et al. 1997) which give similar values for the extinction.

In the Milky Way, there is another, direct way to measure extinctions to individual stars and nebulae. Statistical investigations of the spatial fluctuations of the colour excesses of stars (e.g. Ambarzumian & Gordeladse 1938, Schatzman 1950, Münch 1952, Scheffler 1967) have lead to the concept that the general extinction in the Galaxy is caused by small dust clouds, distributed randomly in space. However, these studies are limited to the solar neighbourhood, up to distances of about 2 kpc, for which they yield a density along the line-of-sight of about 5 clouds per kpc with an average of $A_V = 0.2$ mag per single cloud.

In this paper, we probe the extinction of the Galaxy on a global scale, using 271 planetary nebulae of the bulge as background illumination. Ionized gaseous nebulae. This allows an accurate determination of the extinction from the observed ratio of the Balmer emission lines. The observed decrease of extinction with increasing latitude of the objects allows to define an average model in the form of an homogeneous dust disk and the determination of its optical thickness. Moreover, the scatter about the mean relation serves as a test whether the small clouds model is also valid over large distances. Then we develop a generalized version of the small clouds model as a statistical model for the extinction in disk galaxies, and we discuss the properties of such galaxies, as would be observed from the outside.

2 OBSERVATIONAL SAMPLE

Planetary nebulae – and other ionized nebulae – are ideal for measuring the galactic extinction, as it can accurately be derived from the observed ratio of the Balmer emission lines, whose emissivity ratios are well known and practically independent of the physical conditions (electron temperature and density) in the nebula shell. Furthermore, planetaries usually do not have significant internal extinction (cf. Köppen 1977), so one has a very good measure of the interstellar extinction itself. While nebulae of the disk cannot be used because of their poorly known individual distances, a rather good opportunity presents itself with the 271 nebulae that are identified as belonging to the bulge. They are all within about 2 kpc of the Galactic centre and form a background illumination against which the extinction in the disk can be investigated.

The planetary nebulae in the galactic bulge are taken from the list of Acker et al. (1991), which were selected for having an angular diametre smaller than 20 arcsec and a 6 cm radio flux larger than 100 mJy. Even though a couple of disk nebulae might still be included, the strong concentration of the objects in two regions north and south of the galactic equator (Fig. 1) leaves no doubt that they belong to the bulge. The intensities of the Balmer lines are taken from Acker et al. (1991) for 220 nebulae, which are analyzed with the plasma diagnostic code HOPPLA (cf. Acker et al. 1989), for 21 more nebulae we taken the results of Samland et al. (1992). These data from the spectrophotometric survey are complemented by results based on better spectra taken for individual abundance studies: 13 objects from Aller & Keyes (1987), one nebula each from Barker (1978) and Cuisinier et al. (1996), and two from Kingsburgh & Barlow (1994). For another 13 objects, high quality spectra taken recently by Cuisinier (in preparation) are analyzed with HOPPLA by Leindecker (1996). The combined sample contains 271 nebulae.

Comparison of the observed and theoretical intensity ratios of the Balmer lines, at least of $H\alpha/H\beta$, but usually three or four lines, gives c, the logarithmic extinction measure at $H\beta$ with $c = \lg e \cdot \tau_\beta = 0.4 \cdot A_\beta = 0.35 \cdot A_V$.

Because the theoretical emissivity ratios (cf. e.g. Osterbrock 1974) are almost completely independent of the temperature and density of the emitting gas, the error in c is determined only by the errors in the ratio $r = I_\alpha/I_\beta$ of observed intensities:

$$\Delta c = \frac{\lg e}{A_\alpha/A_\beta - 1} \cdot \frac{\Delta r}{r} \approx \frac{\Delta r}{r}$$

In the observational data used here, the ratio between the fairly strong $H\alpha$ and $H\beta$ lines is often much better than 10 percent, giving an error in c of less than 0.1.

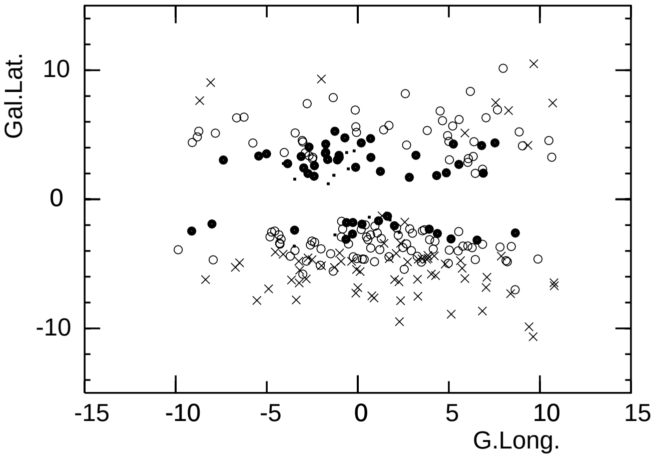

Figure 1. Planetary nebulae of the bulge: filled circles refer to nebulae with high extinction ($c > 2$), open circles to $1 < c < 2$, crosses to $c < 1$, and small dots to faint nebulae ($\lg(F(H\beta)) < -14$).

In Fig. 1 we show the distribution of the nebulae of the sample in the sky. Within about 1 to 2 degrees in latitude of the galactic plane, no bulge nebulae are found, since the very large extinction attenuates their optical fluxes below detection. The sample of detected nebulae is obviously not complete. Since the search for planetaries is not done in a completely systematic and uniform way, one cannot even expect that our sample is statistically representative. On the other hand, comparison with model simulations do not indicate the presence of severe selection effects. Since we shall not derive any absolute or relative numbers of nebulae, this is not a strong restriction to our study. Almost all known galactic planetaries have $H\beta$-fluxes larger than about 10^{-14} erg s^{-1} cm^{-2}, this value may be taken as an average detection limit.

Closest to the galactic plane, one finds heavily reddened nebulae and those below the detection limit, while medium and little obscured nebulae are found at progressively larger latitude. This contrasts with the independence in longitude: We look at the bulge through a flat disk of extinction in the galactic plane. But one also notes in the northern group a lack of low-extinction nebulae.

The systematic decrease of extinction with increasing latitude is depicted in Fig. 2 for all nebulae regardless of their longitude. In both the northern and southern nebulae there are quite well-defined average relations. The more numerous southern subsample exhibits a smaller dispersion. As one would expect, nebulae with small $H\beta$-fluxes have rather large extinctions. Together with the paucity of highly obscured objects this shows the effect of the detection limit among the nebulae. The presence of less obscured but faint

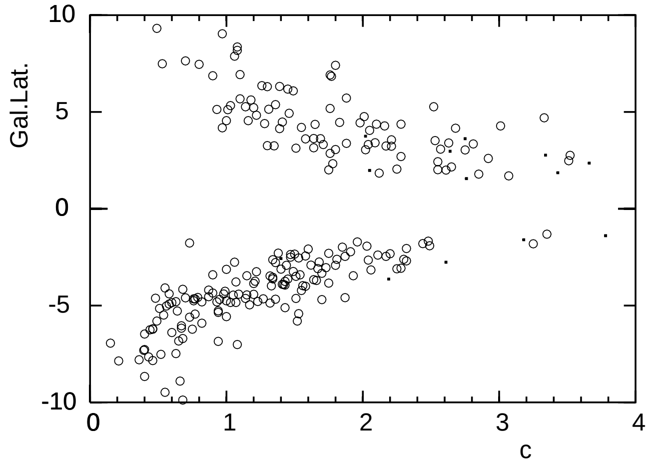

Figure 2. The relation between extinction c and Galactic latitude for the planetary nebulae of the bulge. Small dots indicate the faint nebulae ($\lg(F(\mathrm{H}\beta)) < -14$).

nebulae would be expected from the spread of luminosities during the nebula evolution.

It is worth emphasizing that the absence of highly reddened nebulae at high latitudes is not an observational selection effect: If there were such kind of bulge nebulae, they would surely have been picked up and their extinction been measured with the present detection limit. In the relevant regions in the sky foreground disk planetaries are seen with no indication of a lower number density. The selection criteria of the bulge objects in the region close to the Galactic centre are angular diametre and radio flux, thus neither the extinction nor latitude is involved.

In the northern group the strong paucity of low-extinction objects $c < 1$ is quite marked, and despite the larger scatter, nebulae of the same absolute latitude tend to have higher extinctions (by about 0.2 ... 0.3) than the corresponding southern objects. This reflects nothing but the well known fact that the central dark lane of the Milky Way passes the galactic centre about 5^o north of the equator. This region is rich in dark clouds (Lynds 1968). The lack of low-extinction nebulae as well as the generally shifted $b - c$ relation indicates that the obscuring matter is relatively close to the sun. This northern concentration of obscuring matter could be the result of e.g. a local corrugation of the gaseous disk. The models that are discussed below have been computed with the assumption that the dust disk is inclined against the galactic disk proper. A slight inclination (1^o) suffices to fit well the $b - c$ relations for both subsamples. In this paper, we are shall not pursue this study of the detailed structure of the dust disk, but rather concentrate on the global aspects.

3 COMPARISON WITH HOMOGENEOUS DUST DISKS

A first interpretation of the mean extinction-latitude relation is done by assuming that the dust is distributed in a double exponential disk, i.e. the density n_d depends on distance r from the axis of rotation and height z above the galactic disk:

$$n_d(r, z) = n_\odot \exp(-(r - \mathrm{R}_\odot)/R - |z|/H) \tag{1}$$

with the radial scale length $R = 4.5$ kpc and the scale height $H = 0.14$ kpc (from Bienaymé et al. 1987). For such a model, the column density of dust along a line of sight of latitude b and at longitude $l = 0$ from the sun to the bulge is easily calculated:

$$N(b) = n_\odot \frac{1 - \exp(\mathrm{R}_\odot/R_0 - \mathrm{R}_\odot \tan(b)/H)}{\sin(b)/H - \cos(b)/R_0} \tag{2}$$

Multiplication with the opacity gives the extinction measure c, as a function of latitude. For convenience, we shall refer the densities and opacities to the interstellar gas, using a mass density of the gas at the solar radius ($\mathrm{R}_\odot = 8.5$ kpc) of $n_\odot = 0.04\,\mathrm{M}_\odot/\mathrm{pc}^3$ from Bienaymé et al. (1987).

The average extinction-latitude relation – for the southern group – is well reproduced with an opacity (in terms of c) of $\kappa = 0.01\ \mathrm{M}_\odot^{-1}\ \mathrm{pc}^{-3}$. This gives over a pathlength of 1 kpc in the solar neighbourhood an extinction of $c = 0.4$ or in the visual $A_\mathrm{V} = 1.14$ mag. Hence, the reference value of 1 mag/kpc is in very good agreement with the average extinction seen between here and the galactic bulge.

The shape of these curves depends somewhat on scale-height H and radial scale R of the dust disk (as shown in Fig. 3). It is possible to fit the mean curve by any combination of (κ, R, H) from a rather wide range of values. Demanding a match at three points, a best fit can be found with the reference model (0.01, 5 ± 2, 0.14 ± 0.01) but also for example with (0.03, 25 ± 5, 0.06 ± 0.01) as well as with (0.002, 2.5 ± 0.05, 0.25 ± 0.01) – the error bars being simple eye-estimates. The scaleheight is always well determined, but the radial scale is poorly determined when large, as can be seen from Fig. 3. For the number of the objects and the strong scatter in the data, applying a more refined statistical method does not seem sensible. We prefer the solution (0.01, 4.5, 0.14) as being close to the scaleheight of the neutral gas. But we note that for the radial scale any value in the range $R = 3...10$ kpc would be acceptable, even a value of $R = 2.5$ kpc found for the stars by Robin et al. (1992). Though such short scales would require an uncomfortably large scaleheight for the dust disk.

The same model parameters can also explain the northern nebulae, if one assumes either a foreground extinction of $c = 0.2...0.3$ or that the dust disk is inclined against the galactic plane by about 1^o to the north.

4 DISPERSION OF THE EXTINCTION

The scatter about the average $b - c$ relations is much larger than the dispersion due to observational uncertainties (about $\Delta c \leq 0.1$ and $\Delta b \ll 0.1^o$), and therefore it reflects a genuine property of the interstellar medium. The classical model to explain the spatial fluctuations of the colour excesses of stars in the solar neighbourhood is that of small dust clouds, distributed randomly in space (e.g. Schatzman 1950, Münch 1952). As a consequence, the number of clouds encountered along the line-of-sight follows a Poisson distribution, so the dispersion σ_N^2 is equal to the average value

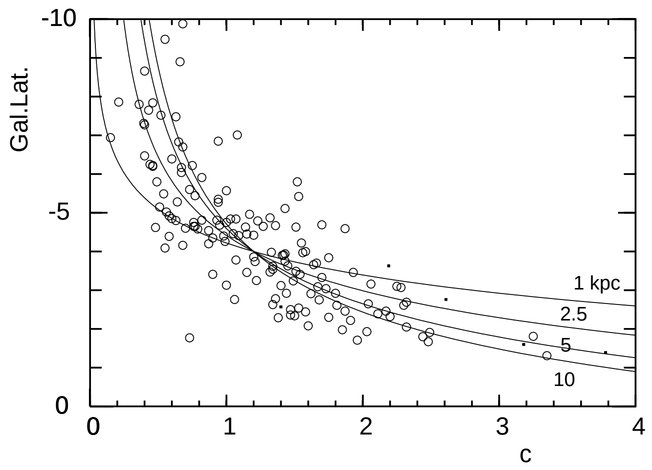

Figure 3. Like Fig. 2, but only for the southern part and in comparison with homogeneous dust disk models with 0.14 kpc scale height and several values for the radial scale.

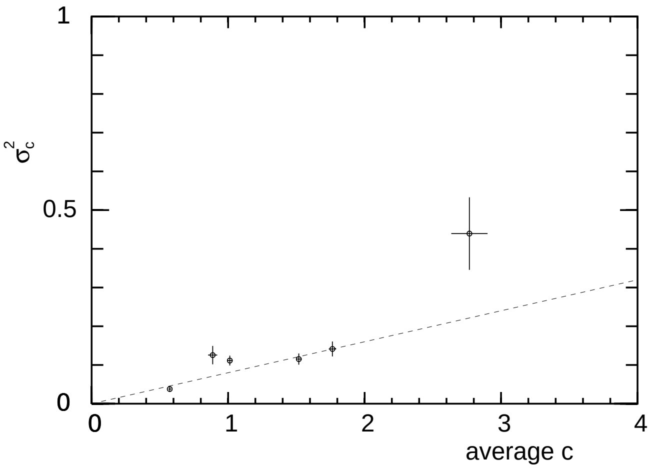

Figure 4. Dispersion and average extinction, computed for nebulae in groups of 1^o-strips in latitude south of the Galactic plane. The dotted line corresponds to clouds with 0.2 mag visual extinction.

$\langle N \rangle$. With the extinction $c_{\rm cloud}$ per cloud, one gets a linear relation between the dispersion and average extinction:

$$\frac{\sigma_c^2}{\langle c \rangle} = \frac{c_{\rm cloud}^2 \sigma_N^2}{c_{\rm cloud} \langle N \rangle} = c_{\rm cloud} \qquad (3)$$

which can be used as a direct measure of the extinction per cloud. In Fig. 4 we show the dispersion and average extinction of the nebulae that are contained in each 1^o-strip of latitude. The obtained points are in reasonable agreement with a straight line corresponding to $c_{\rm cloud} = 0.08$, viz. the 'classical' value of 0.2 mag in visual absorption (cf. Scheffler 1966, 1967). The data from the northern group exhibit a higher dispersion, but also with much larger error bars due to the smaller number of objects in each bin.

Our test shows that this classical statistical description for the the extinction, which was derived from the solar neighbourhood, is well able to account for the scatter in the measured extinctions of objects 8.5 kpc away. Furthermore, there is no need to change the average extinction per cloud from its reference value of 0.2 mag.

5 MONTE CARLO SIMULATIONS

The small number of observed bulge nebulae does not allow reliable statistics with the data itself. Therefore, we performed Monte Carlo simulations for the observed extinctions of a synthetics population of nebulae. Such a flexible approach permits also to incorporate selection effects. Following a given density law, planetary nebulae are placed at random in 3-D space. Each object is assigned certain intrinsic properties, such as Hβ luminosity, mass, radius, expansion age etc. Then, coordinate transformations are performed, distances and extinctions are computed, and any derived quantities are computed, such as observed flux or angular diametre. Finally, the objects are selected according to specified rules, and for the selected nebulae any plots and histograms of observable quantities can be constructed, permitting a direct comparison with the observations.

5.1 A generalized model for the extinction

In the classical model for the solar neighbourhood, the clouds are distributed randomly in space; the average number of clouds on a line-of-sight is proportional to the distance of the star. We shall extend this model by assuming that the number density of clouds varies in space according to an exponential disk (like Eqn. 1). The radial scale $R = 4.5$ kpc and scale height $H = 0.14$ kpc are taken in accordance with the average properties of the dust disk found earlier. As before, we refer to the gaseous disk, with a density in the solar neighbourhood of $n_\odot = 0.04$ M$_\odot$/pc^3. Then it is the column density K which determines the average number of clouds on the line-of-sight: For models with a single type of clouds, we take 5 clouds/kpc with 0.2 mag visual extinction ($c_{\rm cloud} = 0.08$). Comparison with the homogeneous model $c = \langle N \rangle c_{\rm cloud} = K\kappa$ and with $\kappa = 0.01$ one gets

$$\langle N \rangle = K\kappa / c_{\rm cloud} = 0.12 \cdot K \qquad (4)$$

A random number generator for Poisson distributions (from Numerical Recipes) then gives the actual number N of clouds, and hence the extinction value.

The model with two cloud types is done in a similar way, by computing the two average cloud numbers $\langle N \rangle_1 = 0.12K$ and $\langle N \rangle_2 = 0.012K$ to

$$c = 0.08 \cdot N_1 + 0.4 \cdot N_2. \qquad (5)$$

We also computed models which simulate the interstellar medium by a large number of spherical clouds, through which the line of sight may pass. As one would expect, the results obtained are not significantly different from those using the Poisson description, and we find that the planetary nebula data do not pose any strong constraints on the radius or the shape of the clouds, so that the extra amount of computational effort is not deemed worthwhile.

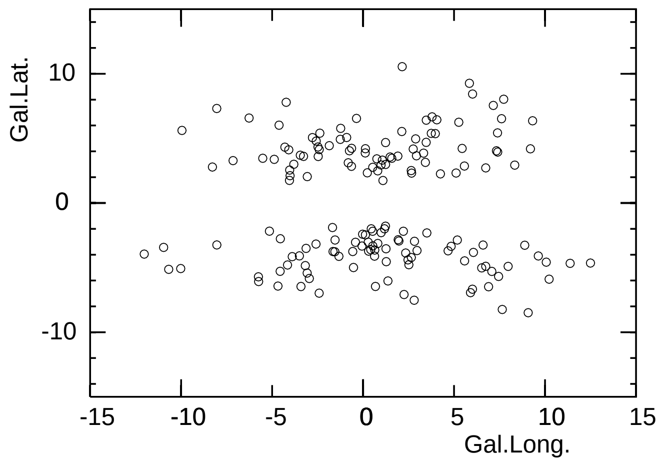

Figure 5. The theoretical distribution of the bulge planetary nebulae which are observable (with $\lg(F(\mathrm{H}\beta) > -14)$.

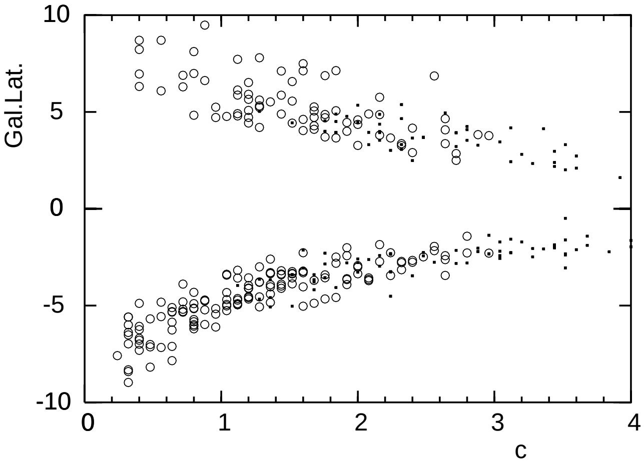

Figure 6. Similar to Fig. 2, but for the extinction model with two cloud types.

5.2 Modelling the bulge nebulae

Since we consider here only the relation between galactic latitude and extinction, the exact modelling of the bulge population is not necessary. Making the bulge larger would shift the simulated objects only towards higher latitudes, but does not change the $b - c$ relation itself. To make the comparison visually more appealing, we however use a reasonable model: the bulge has an oblate ellipsoidal shape, with axial ratios $x : y : z = 1 : 1 : 0.7$. The radial dependence of the density is taken as an exponential function, with a scale length of 0.45 kpc in x and y-direction. This gives a satisfactory representation of the distribution of the nebulae in the sky, shown in Fig. 5. Of course, this model should not be used to compute the fraction of bulge nebulae that are expected to be observable.

To compute the fluxes, we assume that all nebulae have the same luminosity in Hβ of $3L_\odot$. This is chosen to give a good match to the observed distribution of observed fluxes. This is also not an important assumption, because we do not aim to match the measured fluxes. As can be seen in Fig. 6, application of the flux threshold of 10^{-14} erg cm^{-2} s^{-1} gives quite the same effect as in the observational data.

The nebulae are created with random ages between 0 and 50 000 years, and are assumed to expand with a constant velocity of 20 km/s. In the simulations, we select only nebulae with angular diameters smaller than 20 arcsec, just as in the selection of observational data. Again, these reasonable assumptions are not vital for the $b - c$ relation, but assist in making the distribution of model objects along the $b - c$ curve more realistic.

A total of 10000 object are necessary to be generated, in order to obtain about 300 observable nebulae.

5.3 Results

The extinction-latitude relation computed with the generalized cloud model match the observed relations very well. In Figs. 6 and 7 we show the results from the model with two cloud types and with a single type. In both simulations, we introduced a slight inclination of 1^o of the dust disk with respect to the local galactic plane. This accounts rather well for the asymmetry between the northern and southern subsamples. One notes that the extinctions occur only in discrete values, because of the Poisson distribution.

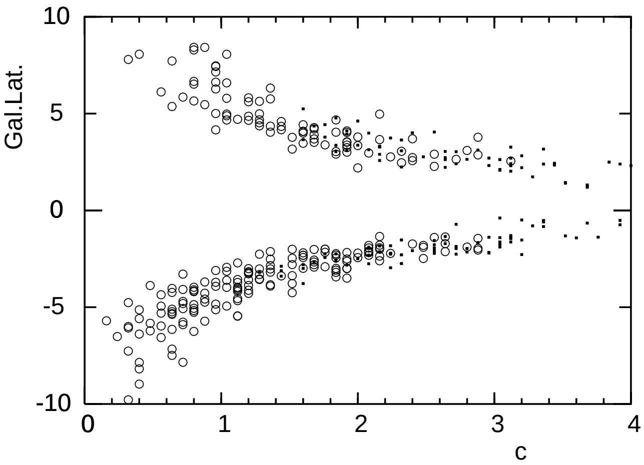

Figure 7. Same as Fig. 6, but for model with a single cloud type.

Not only the mean relation in the southern group is well reproduced, but also the quite well defined distribution of the objects. With respect to the scatter, the model with single cloud species reproduces the observations rather better than the two-cloud-type model which has a smaller scatter. With regard to our small sample of nebulae, we think that is quite acceptable, and we rather refrain from overinterpreting the data. In the simulations, one notes an indention of this curve at about $c = 0.9$ which is due to the occurrence of two opaque clouds on the line-of-sight. The similarity with the indention in the observed data at $c = 0.8$ is of course by chance, and there probably associated with the dark clouds that are reponsible for the obscuration of the northern group.

The relation between mean extinction and dispersion, as computed in strips of equal latitude, is of course perfectly matched, because of the choice of $c_{\rm cloud}$.

5.4 The optical depth of the Milky Way

Taking the dust disk as a exponential disk, thereby neglecting spiral arms and possible corrugations, the mean opacity of 0.01 $\mathrm{M}_\odot^{-1}\ \mathrm{pc}^{-3}$ in c-value gives for the optical depth of the Galactic disk (pole-to-pole, at the centre) of

$$c_0 = 0.74 \quad \text{i.e.} \quad \tau_{\mathrm{H}\beta} = 1.7$$

With a standard extinction curve (Scheffler 1982) this means $A_{\rm B} = 1.9$ and $A_{\rm V} = 1.4$. At the solar radius the disk is transparent, the visual extinction towards the Galactic pole being $A_{\rm V} = 0.1$. One notes, that this is less than the extinction assumed for a single cloud, and due to the Poisson fluctuations, so any value between 0.0 and 0.2 is fully acceptable with the model. Values found in the literature fall well into that range. We have attempted to extrapolate the extinctions seen in disk planetary nebulae at high galactic latitudes, but the paucity of objects and the dominance of close-by nebulae did not permit to arrive at any reliable value.

The model predicts a visual extinction in the Galactic plane to the centre of $A_{\rm V} = 27$ which is in excellent agreement with the observations by Rieke & Lebofsky (1985) of $A_{\rm K} \approx 3$ which corresponds to $A_{\rm V} \approx 30$. This value is confirmed by the results of COBE (Arendt et al. 1994, Weiland et al. 1994) $A_{1.25\mu} \approx 4$ which give $A_{\rm V} \approx 30$.

6 PROPERTIES OF THE EXTINCTION MODEL

The global model for the extinction of the Milky Way can be used to compute how a (hopefully) typical spiral galaxy looks like as seen from outside, and its observational properties. We add to our Monte Carlo simulation a population of stars arranged in an exponential disk with scaleheight H_* and radial scale $R_* = 4.5$ kpc (same as that of the dust disk). To compute the extinction along the line-of-sight of each star and the distant observer, we assume, as before, pure absorption in either a homogeneous disk or a population of very small clouds. The fluxes from all stars are added up, giving the observed galactic luminosity, surface brightness etc.

How the ratio of observable luminosity of a galaxy and its true luminosity changes with optical depth τ_0 (at the galactic centre, pole-to-pole) and on stellar scaleheight, is shown in Fig. 8. Galaxy models with a cloudy extinction are somewhat brighter than models with extinction from a homogeneous disk having the same mean optical depth. Near $\tau_0 \approx 1.7$ this is equivalent to a homogeneous disk having an optical depth only half as large. But apart from this intermediate range, the cloudy models can well be described by their mean optical depths.

The visual light absorbed is reradiated in the infrared. Disney et al. (1989) suggested that if galactic disks were indeed highly opaque, it would be possible to explain the

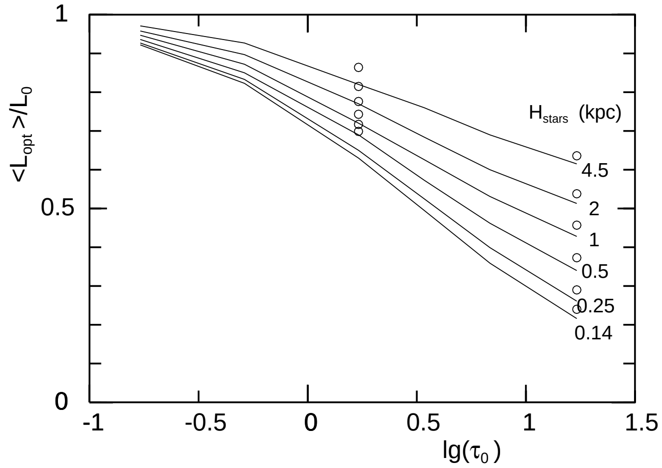

Figure 8. The ratio of the luminosity of the radiation escaping from the galaxy to the one emitted by the stars, computed from homogeneous dust disk model of different optical depths, and for various scale-heights of the stellar disk. The radial scale of both dust and stellar disks is 4.5 kpc, the scale-height of the dust disk is 140 pc. The circles are from the corresponding cloudy models, for our Milky Way model and with a cloud density ten times larger.

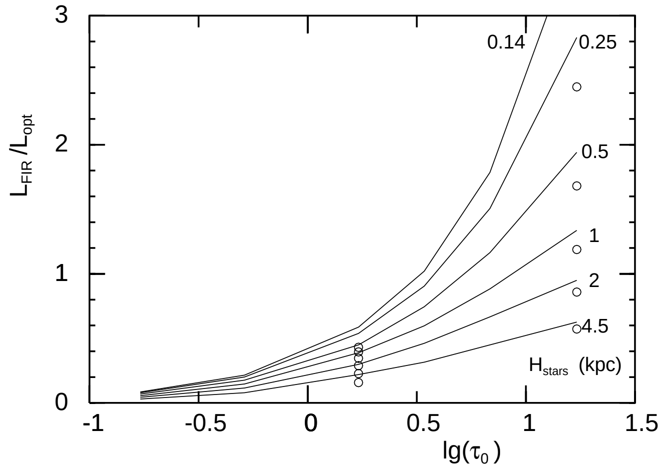

Figure 9. Similar to Fig. 8, but for the ratio of the FIR-luminosity to the optical luminosity.

presence of the very bright infrared galaxies by a normal stellar population. In Fig. 9 we show the ratio of far-IR and optical luminosities. To obtain ratios in excess of say 3, optical depths larger than 10 would be necessary, which is much more opaque than the Milky Way model. One notices that at such large optical depths, the cloud extinction models provide lower ratios than homogeneous disk models.

How much of the light from the stellar population of a face-on galaxy is observed, is depicted in Fig. 10. As before, modeling of the extinction by clouds results in a somewhat brighter galaxy. Because exponential disk models become more transparent in the outer regions, their face-on extinc-

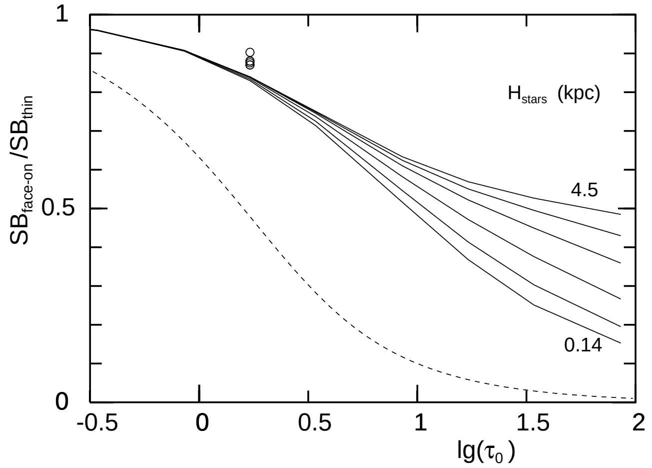

Figure 10. The surface brightness of face-on galaxy models, as a function of the optical depth of the homogeneous dust disk, normalized to the optically thin value. Both dust and stellar disks have the same radial scale of 4.5 kpc, the scale-height of the dust disk is 140 pc. Circles show the results from the cloud models. The dashed curve is the 'uniform slab' model.

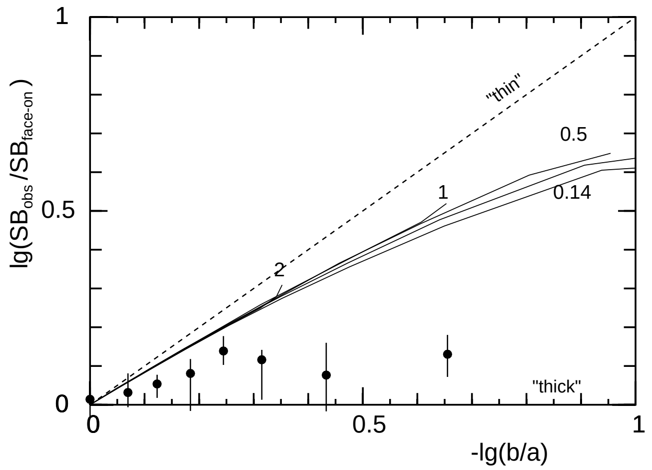

Figure 11. The dependence of the surface-brightness SB on the aspect ratio b/a. SB is normalized to the value for face-on galaxies. Filled dots are the data of Holmberg taken from Fig. 3 of Disney et al. (1989). The full curves are results computed for the Milky Way with the two-cloud extinction model and a dust scale-height of 140 pc, and scaleheights for the stars between 0.14 and 2 kpc. The dashed line show the limiting case for the dust disk being optically thin.

tion is much smaller than that from the 'uniform slab' model of a planar disk of stars and dust well mixed – by more than a factor 3.

Finally, in Figs. 11 and 12 we consider the dependence of surface-brightness on the inclination of the galaxy which is used by statistical studies to infer on the internal optical depth. The ratio b/a of the apparent semi-minor and -major

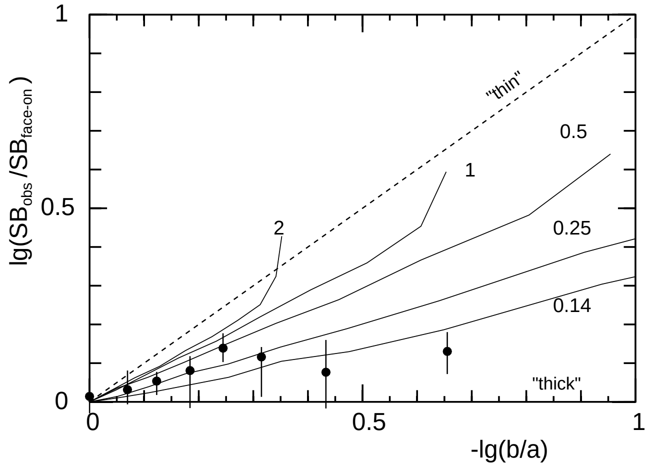

Figure 12. Same as Fig 11, but with densities of both cloud types increased ten times.

axes is computed from the inclination $\cos i$ and the ratio of scaleheight and radial scale

$$(b/a)^2 = (1 - (H/R)^2)(\cos i)^2 + (H/R)^2 \tag{6}$$

In the double logarithmic representation, all curves of constant opacity parameter $n_{\rm eff}$ (cf. Disney et al. 1989) are straight lines through the origin. The limiting cases of optically thin and thick disks are indicated.

Our model for the Milky Way (Fig. 11) gives a behaviour of an optically rather thin galaxy, quite independent of the ratio of star and dust scaleheights. The results shown for models with two cloud types are almost identical to both those done with a single cloud type and for homogeneous disks of the same optical depth. Values for $n_{\rm eff} \approx 0.7...0.8$ are obtained. For comparison, we depict the observations by Holmberg (1975) which would require larger values of the opacity parameter. A tenfold increase of the number densities of both cloud types, results in Fig. 12 showing the much stronger variation of $n_{\rm eff}$ with scaleheight ratio. We do not intend to make an interpretation of Holmberg's original data, but it could be done with a reasonable stellar scaleheight of 250 pc and an extinction ten times larger than in our Galaxy.

In all the models we assume that the extinction is due to pure absorption which is not a realistic assumption for the interstellar dust. Inclusion of scattering – e.g. Corradi et al. (1996) – will result in a reduction of overall extinction, face-on extinction, and will make the galactic disks appear more optically thin.

7 CONCLUSIONS

The individual extinctions derived in 271 planetary nebulae of the Galactic bulge show a systematic decrease with the galactic latitude of the nebulae. The mean relation is well explained by extinction caused by a homogeneous dust disk, with exponential radial scale of about 5 kpc, a scaleheight of 140 pc, and a mean opacity corresponding to a visual extinction in the solar neighbourhood of 1 mag/kpc. In the northern part of the sample, an additional foreground extinction of about 1 mag is present, obviously related to the band of Lynds' dark clouds.

The scatter in the extinction seen for a fixed latitude is well above measurement uncertainties, and is fully compatible with the random scatter expected, if the extinction occurs in unresolved small clouds along the line-of-sight. The 'classical' model elaborated by Schatzman (1950) and Münch (1952) of a population of one or two cloud types, is extended to take into account that the number density of clouds varies like the density in the gas disk, and taking the same parameters. This model is well able to fully explain all properties of the extinctions measured with the bulge planetaries. This is confirmed by Monte Carlo simulations of the nebula population, assuming pure absorption for the extinction.

Scheffler (1966, 1967) was able to show that the observed statistical properties of the fluctuations of stellar colour excesses are well accounted for by applying the two-cloud model to the region inside a radius of 1 kpc distance about the Sun. Outside, the mean extinction seemed to be smaller, but the data also were no longer free of selection effects. Could the model thus be merely a description of the vicinity of the Sun? In our dust disk, the density along a line-of-sight at 1.782^o latitude is constant, thus all distances contribute equally to the extinction. Since our model can reproduce well the observations down to latitudes that low, we conclude that the classical small-cloud model for the interstellar extinction – with the parameters which had been derived for the solar neighbourhood – can well be applied throughout the Milky Way.

The optical depth of the Milky Way, from pole-to-pole at the Galactic centre, is determined as $\tau_{H\beta} = 1.7$, viz. a visual extinction of $A_V = 1.4$. Thus, the Galaxy is a genuinely optically thin galaxy.

The extinction in the plane to the galactic centre is $A_V = 27$, in very close agreement with the measurements of the infrared obscuration (Arendt et al. 1994). Infrared and optical observations of several edge-on galaxies (Wainscoat et al. 1989, Knapen et al. 1991, Jansen et al. 1994) gave apparently lower values $A_V \approx 2$; however, these values need to be corrected for a realistic distribution of stars and dust. For an isothermal disk, Kylafis & Bahcall (1987) derive in NGC 891 an optical thickness of 10.3 in the plane of the whole disk. Aoki et al. (1991) obtain from their observations in H and K for NGC 891 $A_V \approx 7$. Knapen et al.(1991) measure a maximum $A_V = 2$ in the dust lane of NGC 4594 (the "Sombrero"); if we take the conditions at the solar radius (Sect. 5.4), our model gives a visual extinction observable through the inclined (83.5^o) disk of 2.2 mag. Thus the measurements in NGC 4594 – and the other edge-on galaxies as well – are well in accord with an interstellar opacity similar to that of the Milky Way, i.e. in the solar neighbourhood.

Since the only interstellar medium that we know in great detail as its observed properties and its physical processes are concerned, is that of our Galaxy, one might even take it as a typical interstellar medium. In this vein, our extinction model could be taken as a general description for galactic internal extinction. Some properties that would be observed of the Milky Way by an external observer are computed, and they show that one would recognize it as truly optically thin. As one would have surmised, the models with clouds are somewhat more transparent than homogeneous disks. As these calculations are based on the case of pure absorption, they *overestimate* the effects of extinction, any important contribution by scattering would make galactic disks appear even more transparent.

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