The opacity of the Galactic disc derived with planetary nebulae

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ABSTRACT
Planetary nebulae of the Galactic bulge are used as background sources to probe the extinction in the disc. 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 disc similar to the gas disc, with average cloud extinctions taken from the classical models derived from solar neighbourhood stars. The latter models thus also provide an excellent description for the global extinction of the disc. The pole-to-pole extinction of the Milky Way is found to be $A_V = 1.4$, and in the plane one has $A_V = 27$ to the centre, in agreement both with far-IR studies and with individual external galaxies. This indicates that our Galaxy is optically thin, a property shared with other spirals. Observable properties of galactic discs with our extinction model, as would be seen in external galaxies, are presented.

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

1 INTRODUCTION

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

How large is the optical depth of disc 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, Davies & Phillips (1989) emphasized that the behaviour found by Holmberg cannot be interpreted as unambiguous evidence for an optically thin dust disc, 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, Davies & T Minhella (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, Hyland & Freeman 1990; Aoki, Hiromoto & Okamura 1991; Knappen 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 disc. Doing this, Kylafis & Bahcall (1987) derive a visual optical thickness of the whole disc, 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 up to the centre is found to be $A_K = 3$ (Rieke & Lebofsky 1985). With COBE, whose 1.25-μm image nicely shows the thin strip of obscuration in front of the bulge (Weiland et al. 1994), Arendt et al. (1994) deduce $A_{1.25} \approx 4$ which gives $A_V \approx 30$. Also, the far-IR emission from grains can be used to infer 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, more direct way in which to measure extinctions to individual stars and nebulae. Statistical investigations of the spatial fluctuations of the colour excesses of stars (e.g. Ambarzumian & Gerdaladse 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. 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 us to define an average model in the form of an homogeneous dust disc and the determination of its optical...
thickness. Moreover, the scatter about the mean relation serves as a
test as to 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 disc
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, the emissivity
ratios of which are well known and are practically independent of
the physical conditions (electron temperature and density) in
the nebula shell. Furthermore, planetary nebulae usually do not have signifi-
cant internal extinction (cf. Köppen 1977), so that one has a very
good measure of the interstellar extinction itself. While nebulae of
the disc 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 disc can be
investigated.

The planetary nebulae in the Galactic bulge are taken from
the list of Acker et al. (1991), the members of which were selected for
having an angular diameter smaller than 20 arcsec and a 6-cm radio
flux larger than 100 mJy. Even though a couple of disc 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
analysed with the plasma diagnostic code HOPPLA (cf. Acker et al.
1989); for 21 other nebulae we take the results of Samland et al.
(1992). These data from the spectrophotometric survey are com-
plemented 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, Acker & Köppen
(1996), and two from Kingsburgh & Barlow (1994). For another 13
objects, high-quality spectra taken recently by Cuisinier (in prepara-
ton) are analysed with HOPPLA by Leindecker (private
communication). The combined sample contains 271 nebulae.

Comparison of the observed and theoretical intensity ratios of the
Balmer lines, at least of Hα/Hβ, but usually of three or four lines,
gives c, the logarithmic extinction measure at Hβ with

\[ c = \log e 	imes \tau_{\beta} = 0.4 \times A_{\beta} = 0.35 \times A_V. \]

Because the theoretical emissivity ratios (cf. 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:

\[ \Delta c = \frac{\log e}{A_\alpha/A_\beta - 1} \times \frac{\Delta r}{r} = \frac{\Delta r}{r}. \]

In the observational data used here, the ratio between the fairly
strong Hα and Hβ lines is often much better than 10 per cent, giving
an error in c of less than 0.1.

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 attenu-
ates their optical fluxes below detection. The sample of detected
nebulae is obviously not complete. Since the search for planetary
nebulae (PNe) is not performed in a completely systematic and
uniform way, one cannot even expect our sample to be statistically
representative. On the other hand, comparisons with model simula-
tions 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
PNe have Hβ fluxes larger than about \( 10^{-14} \) erg s\(^{-1}\) cm\(^{-2}\), so 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 slightly
obscured nebulae are found at progressively higher latitude. This
contrasts with the independence in longitude: we look at the bulge
through a flat disc of extinction in the Galactic plane. However, 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 Hβ
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 nebulae

![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 (log(F(Hβ)/F(Hα)) < −14).](https://academic.oup.com/mnras/article-abstract/299/2/567/1019272/figure1)

![Figure 2. The relation between extinction c and Galactic latitude for the planetary nebulae of the bulge. Small dots indicate the faint nebulae (log(F(Hβ)/F(Hα)) < −14).](https://academic.oup.com/mnras/article-abstract/299/2/567/1019272/figure2)
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 bulge nebulae, they would surely already have been picked up and their extinction measured, given the present detection limit. In the relevant regions in the sky foreground disc planeteries 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 diameter and radio flux, thus neither the extinction nor the latitude is involved.

In the northern group, the 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° 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 disc. The models that are discussed below have been computed with the assumption that the dust disc is inclined against the Galactic disc proper. A slight inclination ($1^\circ$) suffices to fit the $b - c$ relations well for both subsamples. In this paper, we do not pursue this study of the detailed structure of the dust disc, but rather concentrate on the global aspects.

### 3 COMPARISON WITH HOMOGENEOUS DUST DISCS

A first interpretation of the mean extinction–latitude relation is achieved by assuming that the dust is distributed in a double exponential disc, i.e. the density $n_\odot$ depends on distance $r$ from the axis of rotation and height $z$ above the Galactic disc:

$$n_\odot(r, z) = n_\odot \exp[-(r - R_\odot)/R - |z|/H]$$

with the radial scalelength $R = 4.5$ kpc and the scaleheight $H = 0.14$ 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:

$$N(b) = n_\odot \left| 1 - \exp[-(R_\odot/R_\odot - R_\odot \tan(b)/H)] \right| \frac{\sin(b)/H - \cos(b)/R_\odot}{(R_\odot/R_\odot - R_\odot \tan(b)/H)}.$$  \hspace{1cm} (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 ($R_\odot = 8.5$ kpc) of $n_\odot = 0.04 M_\odot$ 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 $\kappa$) of $\kappa = 0.01 M_\odot$ pc$^{-3}$. This gives, over a pathlength of 1 kpc in the solar neighbourhood, an extinction of $c = 0.4$, or in the visual $A_V = 1.14$ mag. Hence, the reference value of 1 mag kpc$^{-1}$ is in very good agreement with the average extinction seen between here and the Galactic bulge.

The shape of these curves depends somewhat on scaleheight $H$ and radial scale $R$ of the dust disc (as shown in Fig. 3). It is possible to fit the mean curve by any combination of ($\kappa$, $R$, $H$) 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, $5 \pm 2$, 0.14 $\pm 0.01$) but also for an example with (0.03, 25 $\pm 5$, 0.06 $\pm 0.01$) as well as

![Figure 3](https://academic.oup.com/mnras/article-abstract/299/2/567/1019272/fig3)

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

with (0.002, 2.5 $\pm 0.05$, 0.25 $\pm 0.01$) – 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. However, 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, Crézé & Mohan (1992), although such short scales would require an uncomfortably large scaleheight for the dust disc.

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 disc is inclined against the Galactic plane by about $1^\circ$ to the north.

### 4 DISPERSION OF THE EXTINCTION

The scatter about the average $b - c$ relations is much larger than the dispersion resulting from observational uncertainties (about $\Delta c \leq 0.1$ and $\Delta b \leq 0.1$), and therefore it reflects a genuine property of the interstellar medium. The classical model with which 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 $\sigma_c^2$ is equal to the average value $\langle N \rangle$. With the extinction $c_{cloud}$ per cloud, one gets a linear relation between the dispersion and average extinction,

$$\frac{\sigma_c^2}{c} = \frac{c_{cloud}^2 \sigma_N^2}{c_{cloud}^2 \langle N \rangle} = c_{cloud},$$

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° strip of latitude. The obtained points are in reasonable agreement with a straight line corresponding to $c_{cloud} = 0.08$, e.g. 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 as a result of the smaller number of objects in each bin.

Our test shows that this classical statistical description for the
Figure 4. Dispersion and average extinction, computed for nebulae in groups of 1° strips in latitude south of the Galactic plane. The dotted line corresponds to clouds with 0.2 mag visual extinction.

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 using the data alone; therefore, we performed Monte Carlo simulations for the observed extinctions of a synthetics population of nebulae. Such a flexible approach also permits us to incorporate selection effects. Following a given density law, PNe are placed at random in 3D 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 diameter. 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 disc (as in equation 1). The radial scale $R = 4.5$ kpc and scaleheight $H = 0.14$ kpc are taken in accordance with the average properties of the dust disc found earlier. As before, we refer to the gaseous disc, with a density in the solar neighbourhood of $n_C = 0.04$ 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 cloud, we take 5 cloud kpc$^{-1}$ with 0.2 mag visual extinction ($c_{\text{cloud}} = 0.08$). Comparison with the homogeneous model $c = \langle N \rangle c_{\text{cloud}} = K \kappa$ and with $\kappa = 0.01$ one gives

$$\langle N \rangle = K c_{\text{cloud}} = 0.12 \times K.$$  \hspace{1cm} (4)

A random number generator for Poisson distributions (Press et al. 1988) then gives the actual number $N$ of clouds, and hence the extinction value.

The model with two cloud types is determined 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 $c = 0.08 \times N_1 + 0.4 \times N_2$. \hspace{1cm} (5)

We also computed models which simulated 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 were not significantly different from those acquired 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.

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, however, we 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 scalelength of 0.45 kpc in the $x$ and $y$ directions. 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 3 L$_\odot$. 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 the same effect as in the observational data.

The nebulae are created with random ages between 0 and 50 000 yr, and are assumed to expand with a constant velocity of 20 km s$^{-1}$. 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 10,000 objects must be generated in order to obtain about 300 observable nebulae.

5.3 Results

The extinction–latitude relation computed with the generalized cloud model matches 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 $1^\circ$ of the dust disc 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.

Not only is the mean relation in the southern group well reproduced, but also the distribution of the objects is quite well defined. With respect to the scatter, the model with a 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 prefer to refrain from overinterpreting the data. In the simulations, one notes an indention of this curve at about $c = 0.9$ which is a result of 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 a coincidence, and is probably associated with the dark clouds that are responsible 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 $c_{\text{cloud}}$.

5.4 The optical depth of the Milky Way

Taking the dust disc as an exponential disc, thereby neglecting spiral arms and possible corrugations, the mean opacity of $0.01 M_\odot^{-1} pc^{-3}$ in $c$-value gives an optical depth of the Galactic disc (pole-to-pole, at the centre) of $c_0 = 0.74$, i.e. $T_{18} = 1.7$.

With a standard extinction curve (Scheffler 1982) this means $A_B = 1.9$ and $A_V = 1.4$. At the solar radius the disc is transparent, the visual extinction towards the Galactic pole being $A_V = 0.1$. One notes that this is less than the extinction assumed for a single cloud, and is a result of the Poisson fluctuations, so that 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 disc planetary nebulae at high galactic latitudes, but the paucity of objects and the dominance of close-by nebulae did not permit us to arrive at any reliable value.

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

6 Properties of the Extinction Model

The global model for the extinction of the Milky Way can be used to compute what 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 disc with scaleheight $H_\ast$ and radial scale $R_\ast = 4.5$ kpc (same as that of the dust disc). 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 disc 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 $t_0$ (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 disc having the same mean optical depth. Near $t_0 \approx 1.7$ this is equivalent to a homogeneous disc 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 discs were indeed highly opaque, it would be possible to explain the 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 disc models.

Fig. 10 shows how much of the light from the stellar population of a face-on galaxy is observed. As before, modelling of the extinction by clouds results in a somewhat brighter galaxy. Because exponential disc models become more transparent in the outer regions, their face-on extinction is much smaller than that from the ‘uniform slab’ model of a planar disc of stars and dust well mixed – by more than a factor of 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 the internal optical depth. The ratio $b/a$ of the apparent semi-minor and semi-major axes is computed from the inclination $\cos i$ and the ratio of scaleheight and radial scale:

$$ (b/a)^2 = [1 - (H/R)^2] \cos^2 i + (H/R)^2. $$

In the double logarithmic representation, all curves of the constant opacity parameter $n_{\text{eff}}$ (cf. Disney et al. 1989) are straight lines.
through the origin. The limiting cases of optically thin and thick discs 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 discs of the same optical depth. Values for \( n_{\text{eff}} \approx 0.7-0.8 \) are obtained. For comparison, we depict the observations by Holmberg (1975) which would require larger values of the opacity parameter. A tenfold increase in the number densities of both cloud types results in Fig. 12, showing the much stronger variation of \( n_{\text{eff}} \) 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 the result of pure absorption, which is not a realistic assumption for the interstellar dust. Inclusion of scattering – e.g. Corradi, Beckman & Simonneau (1996) – will result in a reduction of overall extinction, face-on extinction, and will make the galactic discs 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 disc, 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\(^{-1}\). 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 as the density in the gas disc, and taking the same parameters. This model is well able to fully explain all properties of the extinctions measured with the bulge populations. 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 that radius, 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 disc, the density along a line-of-sight at 1\(^{\circ}\)782 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 be applied throughout the Milky Way.

The optical depth of the Milky Way, from pole-to-pole at the Galactic Centre, is determined as \( \tau_{100} = 1.7 \), i.e. 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. 1990; 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 disc, Kylafis & Bahcall (1987) derive in NGC 891 an optical thickness of 10.3 in the plane of the whole disc. 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 'Sombreiro'); if we take the conditions at the solar radius (Section 5.4), our model gives a visual extinction observable through the inclined (83.5\(^{\circ}\)) disc 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 far 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 discs. 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 discs appear even more transparent.

ACKNOWLEDGMENTS

The hospitality of Strasbourg Observatory is gratefully acknowledged by JK. We thank Jon Davies for discussions and Mike Disney for stimulating comments, and Jan Palous for the invitation to a stay in Prague which gave us a chance to do some most fruitful reading. We gratefully acknowledge travel support from the PROCOPE programme.

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