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Discussion: Extinction

6.1 Evidence for anomalous extinction

In an optical and UV analysis of Bulge PNe, Walton et al. (1993) found that $R_V = 2.29 \pm 0.50$, concluding that the reddening law is steeper towards the Bulge. Stasinska et al. (1992, hereafter STAS) and Tylenda et al. (1992, hereafter TASK) discuss methods for determining the interstellar extinction of Galactic PNe and compare the two most frequently used; the Balmer decrement $H\alpha/H\beta$ ratio method and the radio/ $H\beta$ flux ratio method. Like all methods, the Balmer decrement method depends on the adopted extinction curve (or mean interstellar extinction law) which is likely to differ from one region of the Galaxy to another. In addition, it requires good quality optical data acquired by filter photometry, or spectrophotometry that encompasses the full extent of the nebula.

In principle, the radio/ $H\beta$ flux ratio method is directly capable of determining the actual value of $H\beta$ extinction, C_β . However, optical thickness of the nebula can lead to an underestimation of C_β . In addition, the predicted $H\beta$ flux depends on adopted electron temperature and He ionization. Blending of He II Pickering 8 emission (4860 Å) with $H\beta$ (4861 Å) flux also adds a (very) small error. Interferometric radio data is preferred over single dish measurements because of the problem of confusion with other

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sources. Zijlstra et al. (1989) have noted that their VLA fluxes are systematically lower than the results from single dish observations, due to possible cutting off of emission from fainter, extended regions of PNe. However, as noted previously, for subset B these 6 cm radio fluxes would have to be underestimated by a factor of ~ 3 for $\langle R_V \rangle \approx 3.1$. Even if radio fluxes were underestimated by 25 per cent $\langle R_V \rangle$ only increases by ~ 0.25 . Also as noted earlier, subset B excludes PNe with suspect radio fluxes (below 10 mJy or high brightness temperature). Allowing that radio fluxes below 10 mJy are often underestimated for many faint PN (e.g. Pottasch and Zijlstra 1994), strong radio sources still have C_{opt} higher than C_{rad} .

STAS find that for PNe with good quality radio and optical data, the relation between C_{rad} and C_{opt} is not 1:1 and that for greater C , C_{opt} is systematically higher than C_{rad} . As STAS do not find a way to impute this trend to systematic errors in absolute fluxes or purely observational effects, they ask if Bulge PNe behave differently from those in the disc. TASK compared the extinction values C_{rad} and C_{opt} for Bulge and Disk PNe (their figs. 6 to 11), and showed that, for all PNe, C_{rad} becomes systematically smaller than C_{opt} for increasing extinction. They proposed that one of the possible reasons (as mentioned by Cahn et al. 1992) may lie in the value of R_V adopted in the extinction curve. They estimated that $R_V = 2.7$ would bring C_{opt} to a rough agreement with C_{rad} .

Ruling out any effects of dust physically associated with nebulae, the only possibility remaining is that the standard extinction law for the diffuse interstellar medium ($R_V = 3.1$) is not well suited to the different lines of sight to PNe. If the true $H\beta$ extinction is given by C_{rad} then according to STAS, R_V reduces to 2.7. This means that the extinction law corresponding to the line of sight of most PNe is significantly different from that for the diffuse interstellar medium. As discussed in section 5.1, dust particles of radii a , having $2\pi a/\lambda \approx 1$ provide for a λ^{-1} extinction law (Evans 1994), where smaller dust grains shift extinction to shorter wavelengths, so that the visual extinction, A_V , is reduced and therefore the value of $R_V (= A_V/E_{B-V})$. This lower R_V (or smaller dust grain size) applies to both Bulge and Disc PNe. How can this be explained?

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Koppen and Vergely (1998) analysed the optical extinction of 271 Bulge PNe, and found (see their figs. 1 and 2) a mean extinction around $C_{\text{opt}} = 2$, and a systematic decrease of the extinction (from 3.5 to 0.5) with increasing Galactic latitude, as well as a genuine scatter about the relation. Both are accounted for by a model of small dust clouds randomly distributed in an exponential disc. They found an extinction $A_V = 1.4$ in the plane, and $= 27$ to the centre, in agreement with far IR-studies (COBE results).

The standard extinction law for the diffuse interstellar medium is based on observations of O and B stars within a few kpc, but these stars must suffer sufficient extinction to allow measurement of their reddening. This selection effect favours denser regions of the interstellar medium in the Solar neighbourhood. For PNe the lines of sight are longer and could cross a more dilute medium while still giving measurable extinction. A lower value of $R_V (< 2.5)$ could be due to a different size distribution of dust particles (i.e. smaller) in these more dilute regions. For the line of sight toward HD 210121, obscured by the high-latitude cloud DBB 80, Larson et al. (1996, 2000) find $R_V = 2.1 \pm 0.2$, which they attribute to an abundance of small dust grains.

More recently Udalski (2003) presents results of analysis of photometric data of Bulge fields from the Optical Gravitational Lensing Experiment II (OGLE-II, Udalski et al. 2002). He shows R_V in general to be much smaller than that corresponding to the standard extinction curve $R_V = 3.1$, and that it varies considerably along different lines of sight. Popowski (2000) has also suggested that interstellar extinction toward the Bulge might be anomalous. Using CCM's extinction law model, Udalski calculates values for R_V ranging from 1.75 to 2.50 in four small regions of the Bulge. Assumed mean brightness, metallicity distribution, and large differences in the mean distance of red clump giants are all dismissed as unlikely reasons for these highly variable values of R_V . In addition, Sumi (2004) confirms Udalski's anomalous R_V values with measurements of $R_V = 1.9$ to 2.1, based on two-band photometry of red clump giant (RCG) stars in OGLE-II VI maps of the Galactic bulge.

My results confirm these previous findings, and I find evidence for even lower values of R_V . I believe my flux and extinction determinations to be accurate because:

the observed $H\alpha$ fluxes are based on filter photometry; catalogue $H\alpha$ and $H\beta$ flux ratios are normally based on single spectra and are unlikely to suffer from systematic errors (even if the absolute fluxes are in doubt); and although catalogue radio fluxes are less certain, I have used a more reliable subset of Bulge objects ($S_\nu > 10$ mJy and $T_b < 10^3$ K) for calculating values for R_V and ΔR_V . However, radio fluxes should be remeasured to obtain the most accurate value for R_V . My mean value of $\langle R_V \rangle = 2.0$ provides further evidence that most lines of sight towards the Bulge cross a less dense medium containing smaller dust grains. It may be the case that the standard extinction law for the diffuse interstellar medium only applies to the local region within a few kpc of our Sun.

6.2 Extinction and the warm ionized medium

The PNe in the Bulge subset B sample have extinction up to $A_V \approx 5$. The usual conversion between extinction and hydrogen column density, assuming $R_V = 3.1$ (Bohlin et al. 1978), is

$$N(\text{H})/A_V = 1.9 \times 10^{21} \text{ atoms cm}^{-2} \text{ mag}^{-1}, \quad (6.1)$$

which gives column densities up to 10^{22} cm^{-2} . For a line of sight of 8 kpc, the average density becomes $n_{\text{H}} \leq 0.4 \text{ cm}^{-3}$ (or 0.6 cm^{-3} if $R_V = 2.0$).

Table 6.1 lists components of the interstellar medium: Molecular clouds; Diffuse clouds; Warm neutral medium (WNM); Warm ionized medium (WIM); and Hot ionized medium (HIM). The warm neutral medium (WNM) has a typical density of $0.1\text{--}10 \text{ cm}^{-3}$, and scale height around 220 pc. The warm ionized medium (WIM) has a typical density of $0.3\text{--}10 \text{ cm}^{-3}$ in the Galactic plane, with a scale height of 1 kpc (Boulares and Cox 1990). The HIM has density below 0.01 cm^{-3} and a scale height of 3 kpc. The WNM, WIM and HIM account for most of the volume in the Galactic disc. The WNM is absent near the Sun (within 100 pc in most directions): the local volume is filled with a HIM with embedded cold clouds.

My extinction values of $A_V \leq 5$ mag suggest that the lines of sight do not intercept

Table 6.1: Components of the interstellar medium.

ISM component	Temperature (K)	Density (cm^{-3})	Scale height (kpc)
Molecular clouds	10	10^4	
Diffuse clouds	10^2	10^2	
Warm neutral medium (WNM)	$10^3 - 10^4$	0.1 – 10	0.22
Warm ionized medium (WIM)	10^4	0.3 – 10	1
Hot ionized medium (HIM)	10^6	< 0.01	3

dense molecular clouds. The density in the HIM is too low to give appreciable extinction even out to the Bulge. The extinction to the Bulge PNe is likely to arise from a mixture of WIM and WNM. The line of sight at higher latitudes leaves the WNM within 2–3 kpc (no Bulge PNe are known within 2 degrees of the plane): the remainder will be mainly within the WIM.

The relation between R_V and C_α depicted in Fig. 5.3 suggests that the lowest R values correspond to the lower density ISM component. A large fraction of the lines of sight fall in WIM-dominated regions above/below the disc. The WNM component is more likely to cause the variable amount of additional extinction. The fact that three PNe located within a degree of each other show very similar – and very low – R_V shows that the low-density structures are similar for line of sights within approximately 100 pc: this provides support for the identification of this component with the WIM. If correct, the distribution of R_V in Fig. 5.3 suggests that the WIM has $R_V \approx 1.5$, and the WNM $R_V \approx 2.5$. The latter value is close to the lowest local values found by CCM.

The anomalous extinction towards the Bulge therefore suggest that the WIM shows smaller dust grains than found in the WNM or molecular clouds. Possible explanations include dust-grain evolution, and the effects of supernovae. The ISM cycles between high-density and low-density phases. If the dust is slowly destroyed during the low-density phases, the size of the dust grains may measure the time since the last high density phase. The large scale height of the WIM suggests its contents may cycle much more slowly.

Supernova-driven shocks can also destroy dust grains. Supernovae are more dominant in the inner galaxy (Heiles 1987): The low-density medium in the inner Galaxy could therefore show systematically smaller dust grains. This would limit the applicability of the standard Galactic extinction curve to quiescent regions of the Galaxy, with steeper curves found in energetic environments.

6.3 Grain sizes

Although different from the locally derived values of R_V , it is possible to show that my low values derived above can be reproduced using dust models. The Greenberg unified dust model (Greenberg and Li 1996; Li and Greenberg 1997) is capable of generating a variety of values of R_V , which encompass the observational value derived in the present work, by varying the turnover radius, a key parameter of the model.

Li and Greenberg (1997) use a three component model to compute the entire interstellar extinction law: large composite grains, small carbonaceous grains and a population of polyaromatic hydrocarbon (PAH) molecules. In the present work, we consider only the large composite grains, which consist of a silicate core and a refractory organic mantle. Addition of the smaller components would tend to increase ultraviolet extinction relative to that in the visible, and thus drive the model results in the present work to smaller values of R_V . The size distribution function used for the composite grains is (Li and Greenberg 1997)

$$n(a) = n_0 \exp \left\{ -5 \left(\frac{a - a_c}{a_m} \right)^q \right\}, \quad (6.2)$$

where $n(a)$ is the number density of grains of total radius a . These composite grains have a silicate core of constant radius, a_c , a mantle of variable thickness, $a - a_c$, and a turnover radius, a_m . The exponent, q , ensures that the distribution of grains falls rapidly for sizes larger than a_m . In the present work values of $q = 2$ are used, as in Li and Greenberg (1997), and $a_c = 0.042 \mu\text{m}$, which was the radius of infinite cylinders in Li and Greenberg, but spheres in the present work.

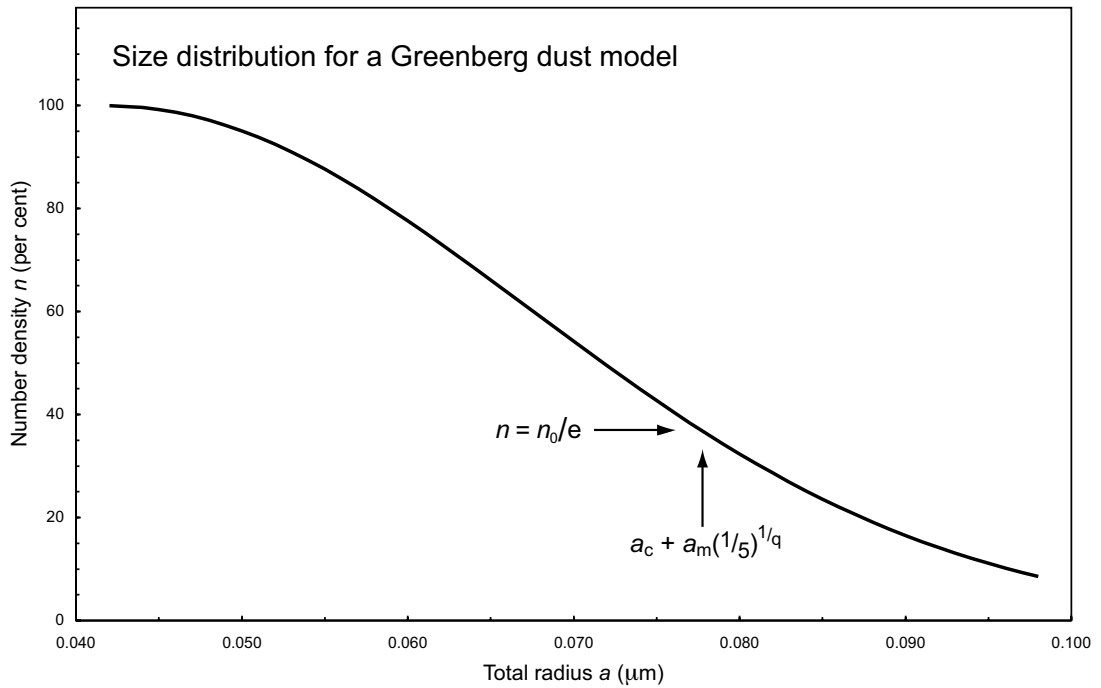


Figure 6.1: Size distribution for a Greenberg dust model, with $n = n_0/e$ indicated, where $a = a_c + a_m(1/5)^{1/q}$.

Fig. 6.1 shows that the ‘peak’ of the distribution is always at $a = a_c$, and that the turnover radius, a_m , is effectively the width parameter of the distribution. The thickness of the mantle, $a - a_c$, over which the distribution falls to $1/e$ of its peak value, is given by $a_m(1/5)^{1/q}$. Therefore, a_m controls the number of large grains per small grain of size $\sim a_c$, as in a rapidly declining exponential, there will be comparatively few grains bigger than a_m , as these fill just the tail of the distribution. The turnover radius is a turnover in probability, not in the shape of the graph, which continues to decline smoothly through a_m .

The value of a_m was varied to generate a table of theoretical values of R_V . The core material used by Greenberg and Li (1996) was based on values for an amorphous olivine (Dorschner et al. 1995). In the present work the olivine is replaced by amorphous forsterite, defined by optical constants (in Scott and Duley 1996), on the grounds that the olivine contains iron, whilst interstellar silicate is now believed to be dominated by magnesium-rich minerals (see, for example, Kimura et al. 2003). Optical constants

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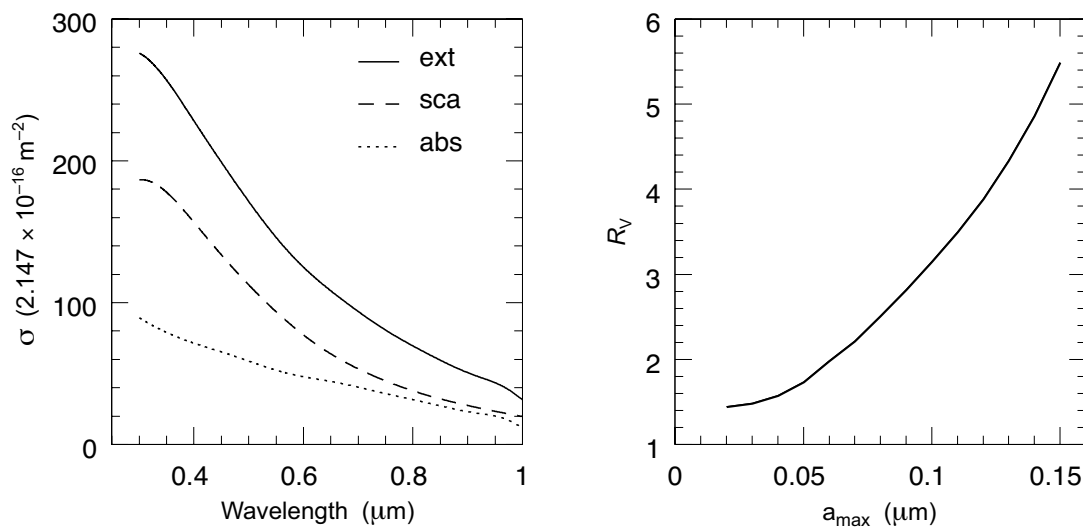


Figure 6.2: (a) A plot, between 0.3 and 1.0 microns, of the absorption, scattering and extinction cross-sections for a Greenberg model with a turnover radius of 0.08 microns, $q = 2$, and core radius equal to 0.042 microns. The cross-sections are measured relative to an area of $2.147 \times 10^{-16} \text{ m}^{-2}$. (b) Calculated values for R_V for a Greenberg dust model, as function of the turnover radius for the size distribution.

for the organic refractory mantle were taken from Greenberg and Li (1996).

Fig. 6.2 (a) shows the optical scattering and absorption coefficients, and the extinction law, for the adopted ‘standard’ model, with one particular value of the turnover radius, $a_m = 0.08 \mu\text{m}$. In Fig. 6.2 (b), the value of R_V is plotted as a function of the turnover radius, a_m . The theoretical values shown encompass all values of R_V from the smallest-but-one of the observational figures obtained in this work, through the rest of the present samples and the more traditional values of ~ 3.1 expected for dust in diffuse clouds, to values in excess of 5, expected for dense, cold, clouds. It should be noted that the key parameter in the model is the amount of grain material found in large grains (with radii larger than $\sim 0.1 \mu\text{m}$). It is also worth noting that, for any value of a_m , a smaller value of R_V may be obtained by adding the populations of small carbonaceous grains and PAHs, whilst a larger value is computable by overlaying the composite grains with layers of ices, as is likely in cold clouds, although as noted in section 6.2, my lines of sight fall mainly within the WIM and WNM. For a comparison of ice-coated and bare grains, see Gray (2001).