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Internal visual extinction in Planetary Nebulae

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Abstract. Except for a very few planetary nebulae, it is usually assumed that intrinsic extinction in such sources is comparatively small, and may be ignored. Such an assumption underpins all previous estimates of nebular distance employing the so-called "extinction" method. We here suggest that extinction may in fact be appreciable for sources having radii $\mathrm{R} < 0.1\mathrm{pc}$, and rise to $\mathrm{C} \sim 2$ where $\mathrm{R} = 8\,10^{-3}\mathrm{pc}$. Such trends are shown to be in reasonable agreement with a simple model of nebular extinction.

Key words: dust; extinction; planetary nebulae; survey

1. Introduction

Although the presence of dust in planetary nebulae is relatively well attested through observations in the near- to far-infrared (e.g. Leene & Pottasch 1988; Pottasch et al. 1984; Phillips & Mampaso 1988; Phillips & Cuesta 1994), and emission by grains has even been seen to extend into the far-red optical spectrum (e.g. Furton & Witt 1992), the evidence for associated visual extinction is very much more restricted. In particular, certain type I/bipolar sources appear to be characterised by high levels of dust opacity, most commonly concentrated towards the nuclei (e.g. Calvert & Cohen 1978; Bohigas, 1994; Phillips et al. 1985), the short-term time variability of which may lead to secular variations in larger-scale nebular structures (Allen & Swings, 1972) or modulations in central star luminosity (Costero et al. 1986, 1993).

For the larger proportion of planetary nebulae, however, it has usually been assumed that such intrinsic components of extinction can be regarded as small or negligible. Such an assumption, in particular, underpins the so-called extinction method for determining nebular distances, whereby comparisons are made between observed nebular extinctions and those of nearby stars of known spectral type (cf. Pottasch 1984). In support of this, Gathier et al. (1986) determined intrinsic extinctions $\mathrm{E}_{\mathrm{B-V}} < 0.06$mag in a subgroup of 13 nebulae for which this procedure was employed.

Is such a presumption true however for all categories of planetary nebulae, and are there particular subgroups (apart from type I sources) for which it would be unsafe to apply such a method?

In the following, we shall propose that there may indeed be evidence for a strong evolutionary variation in visual extinction, and that levels of dust opacity in younger nebulae are often appreciable. Such trends are also shown to be consistent with plausible models of shell expansion.

2. The statistical data base

For the purposes of this analysis we have employed four separate estimates of nebular distances and radii based on two differing statistical procedures. In the first of these, initially extensively developed by Daub (1982), a relationship is established between intrinsic distance and various observable parameters (angular size and radio flux) for a restricted sample of nebulae at "known" distance - that is, for those where (presumably) more reliable distances are available through estimates of spectroscopic parallax, kinematic parallax and so forth. This calibration is then employed to determine distances for a total of 299 further nebulae; an analysis which has subsequently been updated and improved by Cahn et al. (1992; hereafter referred to as CKS) to yield estimates for a yet greater sample (778) of such sources. Van de Steene & Zijlstra (1994; VdSZ) by contrast have employed galactic bulge sources to establish a relation between radio continuum surface brightness T_{b} and distance, thereby enabling a statistical evaluation of distance for some 433 sources, whilst Zhang (1995) employs a synthesis of two related procedures to yield distances which are closely similar to those of VdSZ, but for a larger sample of 647 nebulae.

None of these methods lead to very secure distances for individual nebulae (VdSZ estimate internal errors of ∼40%, whilst Zhang quotes an error range of 35-50%), and the various estimations are clearly far from congruent (viz. the discussion of comparative nebular galactic bulge distributions by Zhang). Comparisons between results based on these differing procedures are nevertheless useful in permitting cross-checks, particularly where anomalies in extinction arise (see later). Such data bases also possess two further appreciable advantages: firstly, that they are extensive, and permit statistically interesting trends in extinction to be evaluated; and second, that none of the data sets depends critically upon extinction measurements, or involve de-

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Send offprint requests to: J.P. Phillips reddening of the observational data base. In this latter respect, however, one minor caveat should be stated: certain of the calibrating nebulae (i.e. those presumed to have well established physical parameters) rely upon distances evaluated through the extinction method; a procedure which we will show to be open to possible error. In most cases, however, the sizes of nebulae so employed are such that levels of internal extinction are likely to be small.

The radii and distances cited above have subsequently been correlated with measures of nebular extinction C tabulated by Tylenda et al. (1992). Following the discussion of these authors we have, in particular, employed values of C deriving from ESO results, and mean estimates culled from the published literature. Radio/Hβ extinctions have not been included, whilst results deriving from the Observatoire de Haute Provence have been employed sparingly.

It has, as a consequence, proved possible to associate extinctions with some 521 nebulae in the Zhang tabulation; with 525 nebulae of CKS; and with rather smaller numbers (367 and 258) for the VdSZ and Daub data sets. Since, in what follows, all four data sets are found to yield essentially similar results, we shall confine our subsequent discussion to the more extensive Zhang and CKS distance/extinction sets.

3. Extinction trends in planetary nebulae

The variation of distance D with extinction C is represented in Fig. 1 for the CKS data set; wherein we have also included a mean trend based on the summary of extinction distances in Pottasch (1984; central diagonal line; flanking diagonal lines correspond to an error of one standard deviation). A compilation of 22 more recent extinction distances from Martin (1994), Kaler & Lutz (1985) and Gathier et al. (1986) yields a broadly comparable gradient $\langle \mathrm{C/D} \rangle \cong 0.36 \pm 0.19$, whilst a comparative analysis for the data points in Fig. 1 yields $\langle \mathrm{C/D} \rangle \cong 0.40 \pm 0.55$. For the CKS and other distance sets, therefore, it would appear that the scatter range in $\langle C/D \rangle$ is considerably greater than would be anticipated from extinction-distance measures; a disparity which is evident from even a casual inspection of Fig. 1, and may reflect comparatively large internal errors in distances D(CKS) as much as the appreciable range of gradients $\mathrm{dC/dD}$ through which the nebulae are observed.

None of the nebular samples for which distances have been evaluated can be in any respect regarded as complete. Thus, for instance, larger nebulae have surface brightnesses which are frequently considerably lower than for less evolved nebulae, leading to difficulties in detection at (in particular) larger distances, where levels of intervening interstellar extinction are also enhanced. As a consequence, there is a bias towards detecting nebulae at small distances D, and mean estimates of distance for nebular radii greater than $\mathrm{R} \sim 0.2\mathrm{pc}$ are correspondingly reduced - as, for that matter, are mean extinctions (see Phillips (1987) for further discussion of this problem, and of the procedures which have been employed to minimise such effects). Similar biases may also influence mean estimates of distance for smaller nebulae, since reduced intrinsic radio fluxes, and difficulties in identification tend to restrict detections and/or distance estimates to relatively closer sources; although it is interesting, in this respect, to note that such trends are more obviously apparent for the CKS/Daub data sets than for the distances of Zhang/VdSZ.

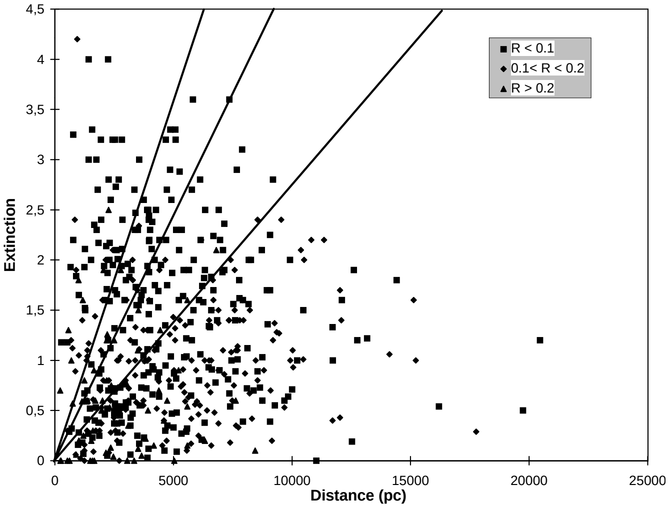

Fig. 1. Representative variation of observed extinction with distances deduced by CKS. The central diagonal line corresponds to a mean trend for the extinction distances tabulated by Pottasch (1994), whilst the flanking diagonal lines correspond to one standard deviation of error

For the following analysis, wherein we evaluate trends of extinction with source radius, we propose to side-step this difficulty by defining a so-called "corrected" extinction ${}^{\mathrm{m}}\mathrm{C}_{\mathrm{corr}}$ for any nebular subgroup m

$$\langle {}^{\mathrm{m}}\mathrm{C}_{\mathrm{corr}} \rangle = \frac{\sum_{i=1}^{m} C_i}{\sum_{i=1}^{m} D_i} \left[\frac{\sum_{i=1}^{n} D_i}{n} \right] \qquad (1)$$

where $\langle D \rangle = n^{-1} \sum_{i=1}^{n} D_i$ is the mean distance for the entire data set n.

Values ${}^{\mathrm{m}}\mathrm{C}_{\mathrm{corr}}$ can be regarded as comparable with the corrected extinction of any other nebular subgroup (say ${}^{\mathrm{k}}\mathrm{C}_{\mathrm{corr}}$) providing the mean associated gradient $\langle \mathrm{C/D} \rangle_m \cong \langle \mathrm{C/D} \rangle_k -$ that is, the distributions of nebular subgroups m and k on the sky are such as to sample available extinction gradients randomly. This, in turn, will arise providing sample numbers m and k are sufficiently large, and the distributions of nebulae upon the sky are reasonably extended.

As an initial application of this procedure, we note that if the results of CKS are divided into two subgroups having $\mathrm{r} \leq 0.08\mathrm{pc}$ and $\mathrm{r} > 0.08\mathrm{pc}$ (yielding corresponding sample numbers $\mathrm{m}(\mathrm{r} \leq 0.08\mathrm{pc}) = 229$; $\mathrm{k}(\mathrm{r} > 0.08\mathrm{pc}) = 296$), then $\langle {}^{\mathrm{m}}\mathrm{C}_{\mathrm{corr}}(\mathrm{r} \leq 0.08\mathrm{pc}) \rangle = 1.53 \pm .06$, and $\langle {}^{\mathrm{k}}\mathrm{C}_{\mathrm{corr}}(\mathrm{r} > 0.08\mathrm{pc}) >= 0.92 \pm .04$. That is, the difference in corrected extinctions between small and larger nebulae

$$\Delta\mathrm{C}_{\mathrm{corr}} =$$

$$\langle {}^{\mathrm{m}}\mathrm{C}_{\mathrm{corr}}(\mathrm{r} \leq 0.08\mathrm{pc}) \rangle - \langle {}^{\mathrm{k}}\mathrm{C}_{\mathrm{corr}}(\mathrm{r} > 0.08\mathrm{pc}) \rangle = 0.61 \pm .07$$

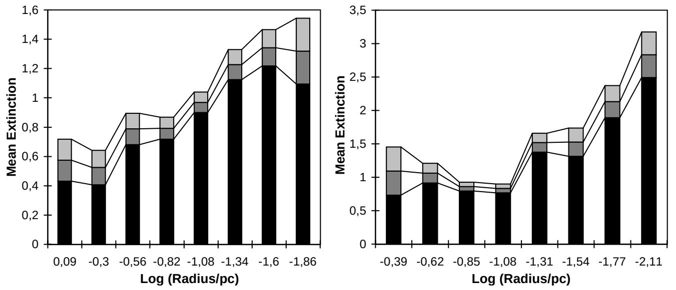

Fig. 2. Variation of corrected extinction with nebular radius (see text), where the lines connecting the bars denote the average extinction (centre lines) and error limits (flanking lines). The right hand panel refers to radii based on the analysis of CKS, whilst the left hand panel corresponds to radii deduced by Zhang (1995). Note, in particular, that the bin centred on $\log(\mathrm{R/pc}) = -2.11$ (right hand panel) represents an average over $\Delta \log(\mathrm{R/pc}) = 0.46$, whereas other bins in this figure are of width $\Delta \log(\mathrm{R/pc}) = 0.23$. Similarly, the bin centred on $\log(\mathrm{R/pc}) = 0.09$ (left hand figure) covers a range $\Delta \log(\mathrm{R/pc}) = 0.52$, whilst other bin widths are $\Delta \log(\mathrm{R/pc}) = 0.26$. Despite some difference in mean extinction, the trends appear broadly similar

Similar values $\Delta \mathrm{C_{corr}} = 0.57 \pm .07$ are obtained using the Zhang data set. It is apparent, in brief, that where nebulae are divided according to intrinsic radius, then there is evidence that smaller nebulae have significantly higher levels of extinction than larger sources.

It is interesting, given this trend, to establish whether anything may be determined about the radius of onset of higher extinctions, and the manner in which extinction varies with radius.

To evaluate this, we have further binned the data sets into nine ranges of $\Delta \log(\mathrm{R/pc})$, as illustrated in Fig. 2. Although the median bin sample numbers are now smaller ($\sim 58\mathrm{bin}^{-1}$), they are still sufficiently large to ensure comparability between differing estimates of $\mathrm{C_{corr}}$, and yield trends with tolerably high levels of statistical significance.

Both sets of results based on the distances of CKS and Zhang yield very similar trends, in the sense that extinction is significantly smaller for larger nebulae ($\mathrm{R} > 0.1\mathrm{pc}$), and increases rapidly to smaller radii (although note that the values of CKS are in all cases systematically larger). This comparability of trends is perhaps more clearly divined in Fig. 3, where we have removed a base extinction from both data sets (assumed to represent the invariant component of interstellar extinction), and compared the results with various model trends to be discussed in Sect. 4. It appears, from this, that both sets of distances (Zhang and CKS) imply a level of excess extinction extending up to $\Delta \mathrm{C_{corr}} \cong 2\mathrm{mags}$ for $\log(\mathrm{R/pc}) = -2$; although given the relatively crude radial binning that we have employed, it is apparent that excesses for the smallest nebulae in these samples are likely to be significantly greater.

It would appear, therefore, that there is a strong prima facie case for supposing that nebulae are associated with significant amounts of intrinsic extinction, and that the level of this opacity increases with decreasing radius.

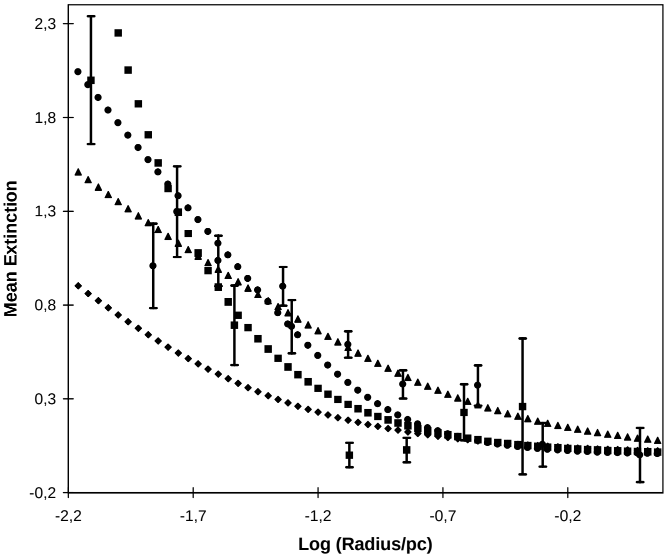

Fig. 3. Variation of "excess" extinction with nebular radius (see text), where the data points correspond to nebular radii based on the procedures of Zhang (1995; black bullets) and CKS (black boxes). In both cases, a constant extinction value has been subtracted from $\mathrm{C_{corr}}$ (Fig. 2), presumed to correspond to a mean value of interstellar extinction; the remaining trend to higher extinctions at small radii is taken to be real, and to arise from dust directly associated with the nebulae. Various models are also illustrated, and described in the text. The lowest curve refers to a model with "standard" parameters, prior to any attempt at fitting, whilst the filled squares correspond to a case where external shell extinction alone is important. The two remaining curves correspond (primarily) to interior shell extinction, and refer to models where U1 is increased over "standard" values by a factor 4.1 (case A; black triangles), and where U1 is decreased by 2.1, and $\gamma + \delta \cong -0.94$ (case B; black bullets)

At this point, it is pertinent to ask whether such levels of extinction are physically plausible; given all that we know about nebular physical properties, is it reasonable to suppose that strong evolutionary trends in extinction might actually arise, and be detectable through observation?

4. Model trends in nebular extinction

Relatively little is known concerning the composition, physical characteristics, and masses of dust residing in planetary nebulae. On the other hand, where regions of higher grain opacity can be discerned, then it appears that they are highly fragmented (as in NGC 7027; Atherton et al. 1979) or strongly concentrated (as in NGC 6302 or NGC 2440; Bohigas 1994; Cuesta & Phillips 1997). Any model of grain opacity which assumes a continuous and homogeneous distribution of grains (as below) can therefore be regarded as only a rather broad approximation, to be employed statistically in investigating appreciable samples of nebulae, or pedagogically in understanding mean extinction trends.

For the purposes of analysing the variations in Fig. 3, we adopt a model whereby PN are characterised by interior ionised cores of constant density $\mathrm{n_1}$ and radius $\mathrm{R_1}$, enveloped by an extended (neutral) shell with density n_2 and radius R_2. Under these circumstances, and assuming a variation in H number density

$$n_2 = n_{20} \left[\frac{R_1}{R} \right]^2 R \geq R_1 \tag{2}$$

then the total Hβ flux received would be given through

$$F(H\beta) =$$

$$0.5 \alpha_\beta h \nu_\beta n_1^2 D^{-2} \int_0^{R_1} a \int_0^{2(R_1^2 - a^2)^{0.5}} e^{-U_1 r_a} dr_a da \tag{3}$$

where integration is carried out over the projected surface of the nebula, and with respect to nebular impact parameter "a" (i.e. projected distance from the centre of the nebula), and displacement r_a along the line of sight through the internal ionised shell. α_β and ν_β are, respectively, the relevant Hβ recombination coefficient and frequency, whilst D is the nebular distance, $U_1 = 1.13\,10^{-21} \mathrm{n}_1 \chi_1$, and χ_1 is the corresponding dust depletion factor. A value $\chi_1 = 1$ denotes opacity levels per unit mass of gas comparable to the ISM, although this parameter may exceed unity as a consequence of enhanced grain formation (e.g. in outflows enriched with nuclear synthesised products), or take values considerably less than unity where spallation and/or sublimation are important. It follows from the above expression that extinction would be given by

$$C_1 = -\log \left[\frac{1}{2U_1} \int_0^{R_1} \mathrm{a} \left\{ 1 - e^{-2U_1 (R_1^2 - a^2)^{0.5}} \right\} \mathrm{da} \right]$$

$$+ \log \left[\int_0^{R_1} a \left\{ R_1^2 - a^2 \right\}^{0.5} da \right] \tag{4}$$

We have so far assumed, in these expressions, that extinction in the external envelope may be regarded negligible. More generally, the total column density of atoms through the outer envelope, projected in front of the ionised zone and along impact parameter a is given by

$$N_2 = n_{20} R_1^2 \int_{(R_1^2 - a^2)^{0.5}}^{R_2} \frac{dR_2}{R_2 (R_2^2 - a^2)^{0.5}} \tag{5}$$

whence extinction of Hβ line emission by the outer envelope alone (and again for impact parameter a) would given through

$$C_2 = U_2 \frac{R_1^2}{a} \left\{ \sec^{-1} \left| \frac{R_2}{a} \right| - \sec^{-1} \left| \frac{(R_1^2 - a^2)^{0.5}}{a} \right| \right\} \tag{6}$$

where

$$U_2 = \left\{ \frac{4.9\,10^{-22} \chi_2 \frac{dM}{dt}}{4 \pi V_2 m_H} \right\} \left\{ \frac{1}{R_1^2} \right\} \tag{7}$$

$\mathrm{dM/dt}$ is the mass-loss rate associated with the outer envelope (assumed to be secularly invariant), V_2 is the expansion velocity, m_H is the atomic mass of hydrogen, and χ_2 is the relevant dust depletion coefficient.

The combined extinctions arising from dust located in both internal (ionised) and external (neutral) envelopes can then be readily shown to be given through a combination of expressions (4) and (6):

$$C = -\log \left[\frac{1}{2U_1} \int_0^{R_1} a (1 - \exp(-2U_1 \{R_1^2 - a^2\}^{0.5})) \right.$$

$$\left. 10^{-\left[\frac{U_2 R_1^2}{a} \left\{ \sec^{-1} \left| \frac{R_2}{a} \right| - \sec^{-1} \left| \frac{(R_1^2 - a^2)^{0.5}}{a} \right| \right\} \right]_{\mathrm{da}}} \right]$$

$$+ \log \left[\int_0^{R_1} a (R^2 - a^2)^{0.5} \mathrm{da} \right] \tag{8}$$

Expression (8) applies where extinction is measured using integrated nebular fluxes in any specified series of transitions (such as the Balmer lines). More realistically, however, many optical determinations of C are based on limited aperture or slit measurements confined to specific locations in the sources (usually the bright nebular cores). For these cases, it is more convenient to adopt a value of extinction appropriate to the projected nebular core; a restriction which simplifies expression (8) considerably to yield

$$C =$$

$$-\log \left\{ \frac{1}{2U_1 R_1} [1 - \exp(-2U_1 R_1)] \right\} + U_2 R_1 \left\{ 1 - \frac{R_1}{R_2} \right\} \tag{9}$$

where the left hand term represents the component of internal extinction, and the term on the right corresponds to "external" extinction arising from the neutral envelope. In what follows, we shall generally assume that $\mathrm{R}_1/\mathrm{R}_2 \ll 1$.

If we now presume an evolutionary variation in n_1 and χ_1 such that

$$n_1 = n_0 \left\{ \frac{R_1}{\mathrm{pc}} \right\}^\gamma \tag{10}$$

$$\chi_1 = \chi_0 \left\{ \frac{R_1}{\mathrm{pc}} \right\}^\delta \tag{11}$$

then from an earlier analysis by Phillips (1984) we find $\gamma = -1.56$. Similarly, Lenzuni et al. (1989) determine a variation in $\mathrm{Ly_c}$ opacity $\propto \mathrm{R}_1^{-1.79}$ which would imply $\delta \approx -0.23$. Finally, assuming the exterior neutral envelope to arise during an earlier OH/IR superwind phase of evolution, with mass-loss rates of order $\mathrm{dM/dt} = 3\,10^{-5} \mathrm{M}_\odot \mathrm{yr}^{-1}$ (Lepine et al. 1995; Baud & Habing 1983), and taking $\mathrm{n}_0 = 17.7$ (Phillips 1984), $\chi_1 = \chi_2 = 1$, and expansion velocities $\mathrm{V}_2 \cong 20 \mathrm{km\,sec}^{-1}$ then yields $\mathrm{U}_2 \cong 2.3\,10^{-22} (\mathrm{R}_1/\mathrm{pc})^{-2}$ and $\mathrm{U}_1 \cong 2\,10^{20} (\mathrm{R}_1/\mathrm{pc})^{-1.79}$.

How does this predicted variation compare with the results determined in Sect. 3? In fact, and as shown by the lower curve in Fig. 3, it appears that we might expect an extinction $\mathrm{C} \sim 0.8$ for $\Delta \log(\mathrm{R/pc}) = -2.2$, compared to an "observed" value which is somewhat more than twice as large, whilst opacity would decrease to very small values where $\mathrm{R} \sim 0.1$ pc (as appears to be observed). Given the simplified nature of this model (and the uncertainties in many model parameters), such a degree of conformity is highly gratifying - it appears, in brief, that a model of nebular extinction using "standard" parameters implies levels of extinction which are comparable to the values actually observed. One may, of course, attempt to tweak the model somewhat so as to obtain improved fits to the "observed" data, and this we have illustrated in the three further curves illustrated in Fig. 3. In the best of these fits (case A) we have increased U_1 by a factor of 4.1, suggesting that either n_0 or χ_0 may require increasing proportionately (i.e. densities and/or grain opacities are greater than supposed above). A second curve (case B) shows the consequence of assuming a steeper decrease in χ_1 and/or n_1 (i.e. $\gamma + \delta \cong -0.94$) and a reduction in U_1 by a factor 2.5 (n_0 or χ_0 *smaller* than assumed in the initial parameters cited above). This, although perhaps less persuasive than the previous fit, is still perfectly acceptable, and suggests that comparatively small changes in the parameters χ_0, n_0, γ, or δ (by a factor of 2 or so) are sufficient to generate reasonable fits to the "observed" data points. We cannot, in brief, determine whether grain opacities per unit mass are required to be greater or smaller than in the ISM, or whether the rate of grain destruction (and opacity decrease) is required to be steeper than presumed from infrared analyses (Lenzuni et al. 1979). It is however apparent that any such departures from "standard" parameters are unlikely to be excessive.

The fits that we have so far discussed are primarily dominated by interior nebular extinction - the exterior (neutral) component is predicted to be small. A reverse case (where internal extinction is proportionately small compared to the outer shell) is illustrated by the trend of filled squares in Fig. 3. In this case, it would appear that the predicted variation is rather steeper than for the observed points, whilst $\chi_2 \mathrm{n}_{20}$ is required to be ~ 32 times greater than supposed above; that is, either grain opacities are substantially greater than supposed for the ISM (suggesting an extremely rich grain formation environment), or (given that velocities V_2 are tolerably correct) that $\mathrm{dM/dt} \propto \mathrm{V}_2 \mathrm{n}_{20}$ has been grossly underestimated. Neither of these options is particularly appetising. In particular, whilst it is likely that mass-loss rates take a broad range of values in pre-cursor OH/IR stars (e.g. Lepine et al. 1995), a value consonant with the analysis above (i.e. $\mathrm{dM/dt} \approx 10^{-3} \mathrm{M}_\odot \mathrm{yr}^{-1}$) would constitute an extreme upper limit.

We are therefore of the view that most of the extinction excesses noted in Fig. 3, and discussed in Sect. 3, are likely to arise from grains located within the ionised zones, where infrared observations have previously confirmed there to be appreciable quantities of warm dust.

5. Conclusions

The presence of observable dust extinction within the shells of planetary nebulae is important for several reasons, not least because it offers a further insight into the physical properties of these ill-defined environments. The present work must in this respect be regarded as a highly preliminary essay, although it is nevertheless useful in suggesting that smaller nebulae are, indeed, preferentially extincted; that the level of this extinction is appreciable ($\Delta \mathrm{C}_{\mathrm{corr}} \sim 2$ for $\mathrm{R} \sim 8\,10^{-3}\mathrm{pc}$); and that the evolutionary decrement in this extinction is rapid, and in conformity with model predictions. Whilst the estimated nebular distances of Daub (1982), Cahn et al. (1992), Van de Steene & Zijlstra (1994) and Zhang (1995) are not particularly accurate, they are at least tolerably independent, and employ two primary procedures for distance determination. It is unlikely, therefore, that similar non-random biases would occur for all four distance sets, and it is indeed difficult to perceive of reasons why such anomalies might arise in any of them.

We therefore conclude that the apparent variation in corrected extinction $\mathrm{C}_{\mathrm{corr}}$ is likely to reflect the presence of a real underlying trend.

Finally, most estimates of distance based on nebular extinction have, heretofore, been confined to nebulae of intermediate radius (say 0.05pc $<$ R $<$ 0.5pc); a size range for which intrinsic extinction is likely to be small. The present work offers a salutary warning not to extend such analyses to smaller nebular radii.

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