The Circumstellar Extinction of Planetary Nebulae

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ABSTRACT

We analyze the dependence of circumstellar extinction on core mass for the brightest planetary nebulae (PNe) in the Magellanic Clouds and M31. We show that in all three galaxies, a statistically significant correlation exists between the two quantities, such that high core mass objects have greater extinction. We model this behavior, and show that the relation is a simple consequence of the greater mass loss and faster evolution times of high mass stars. The relation is important because it provides a natural explanation for the invariance of the [O III] $\lambda$5007 planetary nebula luminosity function (PNLF) with population age: bright Population I PNe are extinguished below the cutoff of the PNLF. It also explains the counter-intuitive observation that intrinsically luminous Population I PNe often appear fainter than PNe from older, low-mass progenitors.

Subject headings: galaxies: individual (M31, Magellanic Clouds) — planetary nebulae: general — stars: AGB and post-AGB — stars: evolution — stars: mass loss

1. Introduction

The modern picture of the formation and evolution of planetary nebulae (PNe) is given by Kwok (1993, 1994). As a star evolves up the asymptotic giant branch (AGB), it loses mass via a slow ($\sim$ 15 km s$^{-1}$) wind at an ever increasing rate. Eventually, a mass loss rate of $\dot{M} \approx 10^{-4}M_\odot$ yr$^{-1}$ is achieved, and during this “superwind” phase, the star
becomes enshrouded by a self-generated circumstellar dust cloud. The mass loss continues until virtually all of the star’s envelope is ejected; when this happens, the hydrogen-burning shell is exposed and the star turns toward the blue in the HR diagram. Shortly thereafter, the core becomes hot enough to ionize its surroundings, and generates a high-speed \( v \sim 1000 \text{ km s}^{-1} \) wind which compresses and shapes the newly born planetary nebula.

A consequence of this evolutionary scenario is that the Balmer lines of young planetary nebulae often show the effects of extinction from dust just outside the ionization radius. Since PN progenitors can be anywhere from \( M \sim 0.9M_\odot \) (Jacoby et al. 1997) to \( \sim 8M_\odot \) (Elson et al. 1998), the amount of dust in the circumstellar region can vary greatly from object to object. Moreover, because the timescale for post-AGB evolution is strongly dependent on core mass, the extent and density of the dust will also be variable. But these dependencies present us with an opportunity: by measuring the extinction in a circumstellar envelope, we can learn about the properties of the progenitor star and thereby constrain models of AGB and post-AGB evolution.

Of course, there are difficulties with this approach, particularly if the targets are planetary nebulae in our own Galaxy. Galactic PNe are notoriously inhomogeneous, and have distance estimates that are extremely poor (cf. Pottasch 1984). Consequently, the intrinsic properties of their central stars cannot be accurately determined. Similarly, in order to measure circumstellar dust around objects in the Galaxy, one must have a good estimate of foreground extinction. Given the non-uniformity of the Galaxy’s cold ISM, this is, at best, a time-consuming task. Finally, because the distances and luminosities of Galactic PNe are uncertain, the precise evolutionary status of many of these objects is controversial. Circumstellar extinction can be expected to decrease with time, as a consequence of nebular expansion. Therefore, unless the objects chosen for study are at roughly the same phase of evolution, the behavior of PN extinction with stellar mass cannot be studied.

The aforementioned problems prohibit us from using Galactic planetaries to explore the systematics of circumstellar extinction. However, moderately large samples of PNe with known distances and foreground reddenings do exist in other galaxies. Specifically, the PNe of the Magellanic Clouds and M31 are excellent candidates for study. Detailed nebular analyses exist for \( \sim 90 \) extragalactic objects, and from these data, it is possible to obtain a large sample of circumstellar extinction measurements and central star mass estimates. Furthermore, since only the brightest PNe in these systems have been measured, most of the objects available for study are at roughly the same stage of evolution. They thus comprise a useful database for our investigation.

Here we examine the behavior of circumstellar extinction with core mass in sets of
planetary nebulae in the Magellanic Clouds and M31. We show that a correlation between core mass and extinction does exist, though it is steeper than what one might predict with simple models. We also show that this correlation provides a natural explanation for the invariance of the planetary nebula luminosity function (PNLF) with population age, as the excess dust extinguishes those PNe that generate [O III] λ5007 fluxes in excess of the PNLF cutoff. This vitiates the conclusion of Méndez et al. (1993) and Méndez & Soffner (1997) that the PNLF cutoff must be brighter in young populations.

2. The Extinction vs. Core Mass Relation

To investigate circumstellar extinction in extragalactic PNe, we restrict ourselves to extragalactic objects whose properties have been derived via full nebular modeling of their emission lines. This effectively limits our sample to two sets of data. For the Magellanic Clouds planetaries, we adopt the Balmer line extinction measurements tabulated by Meatheringham & Dopita (1991a,b) and central star properties derived by Dopita & Meatheringham (1991a,b) and Dopita et al. (1997). These papers provide us with complete information on 73 objects: 57 in the LMC, and 16 in the SMC. (We note that other samples of Magellanic Clouds planetaries do exist, principally through the work of Kaler & Jacoby (1990, 1991) and Jacoby & Kaler (1993). We do not include these data in our analysis, though their use would not affect any of our conclusions.) For M31, we use the extinction estimates and central star parameters of the 15 PNe studied by Jacoby & Ciardullo (1999). To insure homogeneity, all PN core masses were re-computed by taking the central star effective temperatures and luminosities derived from the nebular models, and re-interpolating them onto the grid of hydrogen-burning post-AGB evolutionary tracks given by Schönberner (1983) and Blöcker (1995b). In addition, to place all the extinction measurements on a common system, the contribution of Galactic dust was removed by assuming foreground reddening values of $E(B-V) = 0.080, 0.074,$ and $0.054$ for M31, the LMC, and the SMC, respectively (Burstein & Heiles 1984; Caldwell & Coulson 1985). Here, and throughout the paper, we assume the total extinction at Hβ, $c$, is related to differential extinction by $c = 1.47E(B-V)$ (cf. Kaler & Lutz 1985; Whitford 1958).

Plots of total logarithmic Hβ extinction vs. derived core mass are displayed in Figure 1. From the figure, one immediately notices that there is considerable scatter in the relation. This is not unexpected. Extinction estimates based on measurements of the Balmer decrement may carry an uncertainty of up to $\sigma_c \sim 0.1$ (cf. Ciardullo et al. 1999). This error, plus the error introduced by patchy extinction internal to the parent galaxies (Harris, Zaritsky, & Thompson 1997; Ciardullo et al. 1988) propagates directly into the diagrams.
of Figure 1 and is responsible for the negative reddenings. In addition, most of the PNe plotted in the figure are spatially unresolved, and have not been observed in the ultraviolet. Without the constraints provided by UV line fluxes and nebular morphology, the models are somewhat uncertain, as are the derived positions of the central star in the HR diagram. A further complication is introduced by our use of hydrogen-burning post-asymptotic branch evolutionary models for core mass determinations. Since it is possible for PN central stars to be burning helium, the tracks used in this study may not be applicable for all objects. Finally, even if we had the ability to place each star precisely on the extinction-core mass diagram, there would be intrinsic scatter due to geometry. Most Galactic PNe show a considerable amount of asymmetry (Balick 1987); if the distribution of dust around the bright PNe in our extragalactic sample is similarly asymmetric, then orientation effects alone will broaden the observed relation.

Nevertheless, despite the large amount of scatter, a trend is evident in all three galaxies. The derived core masses of PNe with large Balmer decrements (and therefore large Hβ extinctions) appear to be systematically larger than those with small extinction values. The relation is steep, and there are a few high-core mass PNe in M31 and the LMC that do not obey the rule. But when these outliers \( M > 0.75 M_\odot \) are omitted, the correlations exhibited in all three galaxies are similar. For the LMC data, the slope of the ordinary least squares fit bisector line is 6.3 ± 1.3; for the SMC PNe, this slope is 5.6 ± 0.7, while for M31, the slope is 8.5 ± 1.6. Considering that the metallicities of the objects involved span a factor of \( \sim 10 \), that the ages of the parent populations are drastically different, and that the M31 PN observations, reductions, and analysis were performed completely independently of those done for the Magellanic Cloud PNe, the consistency of the results is striking.

3. The Statistical Significance of the Extinction-Core Mass Correlation

Before proceeding further, it is important to consider the statistical significance of the relations displayed in Figure 1. The measurement errors on extinction and core mass are not independent. If the extinction to a planetary is overestimated, then its absolute emission line flux and the derived luminosity of its exciting central star will be overestimated. Since the luminosity of a young planetary nebula depends only on the mass of its core, an error in one means an error in the other. An artificial correlation between extinction and core mass can then be the result.

To test the significance of the relations displayed in Figure 1, we make the following assumptions. First, we assume that each extinction measurement has an uncertainty of 0.1 in \( c \). This is rather conservative. While Ciardullo et al. (1999) have shown that extinction
estimates to Galactic PNe have a typical error of $\sigma_c \sim 0.1$, this is often due to the effects of atmospheric dispersion and the presence of non-uniformities in the distribution of dust around resolved objects. Because all the PNe considered here are extragalactic, the latter problem is not an issue in this analysis. Moreover, it is likely that errors due to atmospheric dispersion are also not a concern. The M31 data were taken through an atmospheric dispersion corrector, and the Magellanic Cloud PNe were all observed with the slit rotated along the direction of dispersion. An analysis of the higher order Balmer lines in the M31 planetaries suggests that for these objects, the true uncertainty in $c$ is $\sim 0.06$ (Jacoby & Ciardullo 1999). Based on external comparisons, the error in $c$ for the Magellanic Cloud PNe is likely to be similar (Meatheringham & Dopita 1991a,b). Nevertheless, because the uncertainty in $c$ is of critical importance for estimating the reality of the extinction-core mass relation, we choose to be conservative and assign $\sigma_c = 0.1$.

We next assume that any error in the measurement of $c$ affects only one quantity, the derived luminosity of the central star, and that the logarithmic increase (or decrease) in the star’s luminosity is equal to $c$. This is a reasonably valid approximation: although the reaction of a given nebular model to a change in extinction is complex, to first order, the energy emitted at $H\beta$ does reflect the central star’s luminosity. Furthermore, the objects considered in this paper are all extremely bright, and their central stars should still be moving horizontally in the HR diagram. Consequently, the derived mass of a PN core will depend only on the core’s luminosity, not on its effective temperature. Uncertainties in the latter quantity can thus be ignored.

Finally, to test the null hypothesis, we assume that extinction and central star mass are, in reality, uncorrelated. We randomly associate extinction values between 0.0 and 0.8 with central star masses between $0.56M_\odot$ and $0.66M_\odot$, and derive the luminosities of these stars based on the Schönberner (1983) and Blöcker (1995b) evolutionary tracks. We then place a random (Gaussian) error of $\sigma_c = 0.1$ on the extinction, re-derive the core masses using the revised luminosity, and model the observed PNe population of each galaxy via a series of Monte Carlo simulations. Using 10,000 simulations per galaxy, we ask how often our model collection of PNe would have a Spearman rank order coefficient as large, or larger than that observed.

The results for all three galaxies are similar. Under the assumption of a $\sigma_c = 0.1$ measurement error, the LMC correlation is significant at the 95% confidence level, the SMC points correlate with 97% confidence, and the M31 correlation is significant at the 94% confidence level. (In other words, in $\sim 95\%$ of the trials, the Spearman rank order correlation is less than that for the real data). If the error on $c$ is reduced to $\sigma_c \approx 0.06$, which, given the quality of the data is more likely, the significance levels for the LMC
and SMC data rise to 99%, while that for M31 increases to 96%. Changes in the adopted model for the distribution of central star masses and extinctions do not change the result significantly. Thus, despite the scatter, the correlation between extinction and core mass appears to be real. It is extremely unlikely that all three correlations are an artifact of the analysis procedure.

4. Modeling the Correlation

Figure 1 confirms, at least qualitatively, the technique of measuring PN core masses using nebular models and stellar evolutionary calculations. The sign of the correlation is as expected: high mass PN central stars, which presumably come from high mass progenitors, have large amounts of circumstellar matter, and evolve quickly across the HR diagram before their circumstellar matter has time to disperse. Thus, they are heavily reddened. Low core-mass PNe have less of a circumstellar envelope and evolve blueward on much longer timescales. The extinction affecting these objects is correspondingly less.

In addition to having the correct sign, the range of extinction displayed Figure 1 is also within expectations. Hubble Space Telescope images of bright PNe in the Magellanic Clouds shows that the median radius of these objects is $\sim 0.05$ pc (Dopita et al. 1996). If we assume that the circumstellar envelopes obey an $1/r^2$ density law, extend to a radius of $\sim 0.3$ pc (Knapp, Sandell, & Robson 1993), and have a gas-to-color-excess ratio of $\sim 5.8 \times 10^{21}$ atoms cm$^{-2}$ mag$^{-1}$ (Savage & Mathis 1979; Knapp, Sandell, & Robson 1993), then the amount of extinction associated with these objects should typically be several tenths of a magnitude. Again, this is what is observed.

The above calculation can be made more rigorous through the use of AGB and post-AGB evolutionary tracks. To do this, we use the evolutionary tracks of Blöcker (1995a,b), which follow the mass loss and HR diagram evolution of stars with initial masses of 3, 4, 5, and 7$M_\odot$. First, we assume that the stellar mass loss of each model is spherically symmetric, and that the implied AGB wind has an expansion velocity of $\sim 15$ km s$^{-1}$. This allows us to compute the radial profile of a star’s circumstellar envelope at the time when it is becoming a bright planetary. (For the purpose of our calculation, we assume this occurs at $\log T_{\text{eff}} \approx 5.0$.) Next, we adopt the canonical gas-to-color-excess ratio of $\sim 5.8 \times 10^{21}$ atoms cm$^{-2}$ mag$^{-1}$ and assume that the ionization radius of our typical planetary nebula is $\sim 0.07$ pc. This gives us the circumstellar extinction expected as a function of initial mass. Finally, we use the initial-mass final-mass relation implied by the Blöcker mass loss rates to connect the initial stellar mass to the final core mass. With this information, we can simulate the data displayed in Figure 1.
The solid line drawn in the SMC panel of Figure 1 displays the results of this calculation. As can be seen, our simple model does produce an extinction-core mass relation, but with a slope that is significantly smaller than what is observed. Given the amount of physics omitted from the computation, this is not surprising. As the stellar core moves to the blue in the HR diagram, a fast wind develops which compresses the surrounding medium, and alters the distribution of matter close to the star. This clearly is a complexity that is beyond the scope of this paper. Moreover, Type I (Population I) planetaries in the Milky Way are often bipolar (Peimbert & Torres-Peimbert 1983), hence for these objects, the assumption of spherical symmetry is violated. But the most critical shortcoming of the model concerns the definition of the inner radius for extinction. In our models, this value is well defined: extinction is only applied when light has passed the optical boundary of the nebula. However, in real objects, the dividing line between emission and attenuation is not so discrete, and, since the greatest amount of extinction occurs at small radii (where the density of the material is highest), this over-simplification is costly. The solid line of Figure 1 was computed under the assumption that the inner radius for extinction is 0.07 pc; this is the median nebular radius of our sample, as as defined by the nebular models of Dopita & Meatheringham (1991a,b) and Jacoby & Ciardullo (1999). However, as the dotted line of Figure 1 shows, if we adopt an “effective” radius for extinction that is smaller, \( \sim 0.02 \) pc, we can steepen the relation to match the observations. (There is still a constant offset between our model and the data, but this can be rectified in a number of ways, including adjusting the mass ejection rate and/or changing the gas-to-color-extinction ratio.) Unfortunately, without a much more detailed computation of extinction within and around the nebulae, we cannot refine our calculation.

The qualitative agreement between the data and the computed relation is encouraging, as it suggests that a more detailed simulation might be able to provide new constraints on the late stages of stellar evolution. In particular, the amount of circumstellar extinction surrounding a PNe is sensitive to two quantities: the total mass in the circumstellar envelope (and therefore in the progenitor star), and the timescale for post-AGB evolution across the HR diagram. If the amount of matter in the circumstellar envelope can be measured through extinction, it may produce an improved estimate of the initial-mass final-mass relation. Similarly, if the AGB and post-AGB evolutionary timescales can be constrained, it may lead to a better understanding of the planetary nebula phenomenon. Clearly, the extinction core-mass relation offers some intriguing possibilities for probing stellar evolution.
5. The Extinction-Core Mass Relation and the Planetary Nebula Luminosity Function

The relation displayed in Figure 1 has an interesting consequence for the \([\text{O III}] \lambda 5007\) planetary nebula luminosity function and the extragalactic distance scale. Observations of PNe in \(\sim 30\) elliptical, spiral, and irregular galaxies have demonstrated that the PNLF is remarkably insensitive to stellar population (Jacoby et al. 1992; Ciardullo, Jacoby, & Tonry 1993; Feldmeier, Ciardullo, & Jacoby 1997). Models by Jacoby (1989) and Dopita, Jacoby, & Vassiliadis (1992) explain why progenitor metallicity has little effect on the PNLF, but no theory exists for the PNLF’s invariance with population age. In fact, analyses by Méndez et al. (1993), Han, Podsiadlowski, & Eggleton (1994), Jacoby (1996), and Méndez & Soffner (1997) all show that the location of the PNLF cutoff should be brighter in young, star-forming populations. Yet PN surveys in the LMC and three spiral galaxies have detected no such dependence (Jacoby, Walker, & Ciardullo 1990; Feldmeier, Ciardullo, & Jacoby 1997).

Figure 1 explains the age invariance. To first order, the strength of a bright PN’s \([\text{O III}] \lambda 5007\) emission line depends on the amount of energy deposited in the nebula. Specifically, the post-AGB evolutionary models of Schönberner (1983) and Blöcker (1995b) suggest that the maximum \([\text{O III}] \lambda 5007\) flux attainable by a PN should go as roughly the square of its core mass. Since the mass of a PN’s core reflects the mass of its progenitor via the initial mass-final mass relation, this seems to imply that younger populations make brighter planetaries. However, as Figure 1 shows, the increased emission from high core-mass PNe is more than made up for by the increased amount of circumstellar extinction. In fact, the slope of \(\sim 6\) seen in the figure guarantees that Type I planetaries will be fainter than PNe derived from older stars. This effect is not included in any of the theoretical analyses of the PNLF, and explains why the brightest PNe in the LMC and M101 are no brighter than those found in elliptical galaxies.

Figure 2 demonstrates this effect quantitatively. The dotted line in the figure plots the predicted dependence of the PNLF cutoff with population age, under the assumption that circumstellar extinction is not correlated with core mass. This calculation comes from Jacoby (1996), and assumes that a constant fraction (15\%) of the PN central star’s luminosity is reprocessed into \([\text{O III}] \lambda 5007\) emission (Dopita, Jacoby, & Vassiliadis 1992). According to the model, the PNLF cutoff is a sensitive function of population age, with young (\(\sim 1\) Gyr) stars creating planetaries that are \(\sim 1\) mag brighter than PNe formed from old (\(\sim 10\) Gyr) stars. It is therefore in direct conflict with observations of extragalactic PNe. The solid line of Figure 2 shows the same model, except with the effects of circumstellar extinction included via the extinction-core mass relation of Figure 1 (slope
of \( \sim 6 \). With this modification, the model fits the observational constraints extremely well. For populations older than \( \sim 1 \) Gyr, the PNLF is independent of age to within \( \sim 0.1 \) mag, as the increased extinction around higher mass stars is canceled out by the increased central star luminosity. For younger populations, the PNLF cutoff become fainter. However, since real galaxies contain a mix of stellar populations, the brightest PNe observed will always be those from the old and intermediate age stars. Consequently, distance estimates based on the PNLF will not be affected by Population I planetaries.

6. Discussion

Aside from explaining the age invariance of the PNLF, the extinction-core mass correlation has some other interesting consequences. The first involves the location of high core-mass objects on the diagram of Figure 1. Ten objects fall well off the relation defined by the bulk of the planetary nebulae. These PNe are severely under-extincted for their core mass, and, at first glance, their presence seems to imply that the extinction law breaks down for massive central stars. However, an investigation of these objects reveals that only two have derived nebular radii smaller than the median of our sample. According to our simple model, a larger median size should translate into a shallower extinction law. This is consistent with the data.

In fact, it is relatively easy to explain the “anomalous” objects of Figure 1. High core-mass planetaries are born on the main extinction-core mass relation, but their large, thick circumstellar dust cloud prevents them from being identified in extragalactic surveys. Only at a later time, when the envelope has begun to disperse and the optical nebula has grown in size, is the PN available for study. By this time, the central star has completed its trip to the blue in the HR diagram and has begun to fade. Consequently, the PN will not appear “super-luminous” in an \([\text{O III}] \lambda 5007\) survey. However, because the object was extremely luminous to begin with, it will still be bright enough to be detected photometrically, and studied spectroscopically. It will therefore appear to be under-extincted in the extinction core-mass diagram.

We do note that, based on the galaxies’ stellar populations, we would expect to see a larger fraction of high core mass planetaries in the Magellanic Clouds than in M31. Somewhat surprisingly, this does not seem to be the case. Roughly 15% of the PNe in the LMC and M31 are high core-mass objects, while no high core-mass planetaries have been identified in the SMC. The significance of this is difficult to evaluate, since none of the PN samples is in any way statistically complete. Moreover, the absence of high core-mass PNe in the SMC may be due to random chance, since, all things being equal, we would expect
our sample to contain only $\sim 2$ of these objects. Since we know of no selection effect which would prevent us from seeing high core mass PNe in the SMC, the absence of these objects is probably not significant.

Another implication of Figure 1 deals with its potential use for measuring galaxy evolution. Dopita et al. (1997) have shown that it is possible to trace the past star formation and chemical evolution of a galaxy through measurements of its planetary nebulae. One uses the nebular emission lines to determine the effective temperature and luminosity of the central star. Then, with the aid of post-AGB evolutionary tracks, one derives the PN core mass. Once the core mass is known, the age of the progenitor then follows from the initial mass-final mass relation.

The key to this procedure is obtaining the mass of the PN core, and the extinction-core mass relation is another tool for constraining this quantity. Because the scatter in extinction is large, age estimates based on extinction measurements alone will probably not be possible for individual objects. However, the mean extinction of a population of PNe might be a useful tool for estimating age, especially if the measurement is done differentially with respect to the mean of other systems. Further observations will be needed to check this possibility.

We conclude by emphasizing that in order to study the systematics of circumstellar extinction, the sample of objects must be chosen carefully. The analysis in this paper was limited to only the brightest planetary nebulae. Consequently, only newly formed objects near the peak of their UV luminosity were included in the samples. With this restriction, a correlation between extinction and core-mass can be detected. However, as a PN evolves, its nebula expands, its dust envelope disperses, and its circumstellar extinction decreases. Samples of PNe that span a wide range in age will therefore not show the correlation. As a result, PN observations in the Galaxy cannot be used for investigations of this type. As in other fields of study involving planetary nebulae, the best place to investigate circumstellar extinction is in other galaxies.

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Fig. 1.— The variation of extinction (computed from measurements of the Balmer decrement) vs. derived core mass for samples of bright PNe in M31 and the Magellanic Clouds. Although the scatter is substantial, all three galaxies show a statistically significant correlation between circumstellar extinction and core mass. The solid line in the SMC panel is our simple extinction model using a nebular radius equal to that of a median planetary (0.07 pc). The dashed line represents a similar extinction model, but with a radius of only 0.02 pc. The vertical placement of the curves are somewhat arbitrary, in that they depend on the assumed AGB mass ejection velocity and the gas-to-color-extinction ratio.
Fig. 2.— The change in the PNLF cutoff magnitude ($M^*$) as a function of population age. The dotted line shows the prediction of Jacoby (1996), which does not include the effects of circumstellar extinction; the solid line shows the same calculation, but with a slope of $\sim 6$ for the extinction-core mass relation. Note that when circumstellar extinction is included, the PNLF cutoff becomes insensitive to age for populations older than $\sim 1$ Gyr, and that the cutoff for extremely young populations is fainter than that for older systems. Since real galaxies have a mix of stellar populations, the older stars will always dominate the bright end of the PNLF. This helps to explain why the technique of using bright planetary nebulae to measure extragalactic distances works well in both spiral and elliptical galaxies.