PLANETARY NEBULAE AND CHEMICAL EVOLUTION OF THE GALAXY

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1. RELATIONS BETWEEN PLANETARY NEBULAE AND LONG-TERM EVOLUTION

The chemical evolution of galaxies is controlled by star formation, stellar mass loss, gas flows, and the compositions of matter involved in these processes. Planetary nebulae (PN) thus affect chemical evolution directly in representing mass ejection at the end of the nuclear burning lives of many stars, and in enriching the interstellar medium in elements that are overabundant in the nebulae. Supernovae often eclipse PN in discussions of these effects, so it is noteworthy that planetary precursor stars not only provide much of the present stellar mass loss in the solar neighborhood, but also show as clear evidence as supernova remnants for the ejection of elements newly synthesized in the stars themselves. Furthermore, PN are tracers of the past star formation history in a galaxy, since their rate of occurrence depends on the birthrate of progenitor stars during the whole lifetime of the system.

In order to assess the effects of PN on the long-term history of the Galaxy, we need to know their occurrence rate, distribution, shell masses, and chemical compositions. An important point is that the nebula represents only part of the mass lost from its precursor star, so we must also know the initial mass of the precursor, its total mass loss, and the composition of its whole envelope. Because none of these quantities is known definitively, the primary aim of this paper is to illustrate methods and concepts that can be developed in the light of growing knowledge about PN and their precursors.

2. RATES IN THE SOLAR NEIGHBORHOOD

It has often been remarked that the local formation rates of PN and white dwarfs are about equal to each other and to the expected deathrate of low-mass stars (e.g. Salpeter, 1971; Tinsley and Ostriker, 1976; Cahn and Wyatt, 1976). This consistency, together with evidence on Galactic population types, supports the view that stars not massive

Yervant Terzian (ed.), Planetary Nebulae, Observations and Theory, 341-352.

https://doi.org/10.1017/S0074180900143347 Published online by Cambridge University Press

enough to become supernovae eject a PN shell and die as white dwarfs. Some details and implications will be reviewed.

2.1 Predicted rates of occurrence

A prediction of the PN rate requires assumptions about their origins and the past history of star formation. We adopt the hypothesis that one PN is ejected by each dying star in the mass range from the turnoff mass m_t (the mass of a star with lifetime equal to the age of the Galaxy) up to 5 $M_\odot$; uncertainties in the upper limit (Tinsley, 1977a) are unimportant in this context, because replacing 5 $M_\odot$ by any value $\gtrsim$ 3 $M_\odot$ would affect the scale of the calculated PN rate by less than 50% and its time-dependence during only the first few 10^8 years.

The stellar birthrate function may be written, in general, $\psi(t) \times \phi(m)dt\,dm$ = no. of stars born in the time interval (t,t+dt) and in the mass interval (m,m+dm). The initial mass function (IMF), $\phi(m)$, is normalized so that $\psi(t)$ is the total mass of stars born per unit time, i.e. the star formation rate (SFR). Now the PN rate at time t is clearly given by the expression

$$r_{PN} = \int_{m_t}^{5\,M_\odot} \psi(t-\tau_m)\phi(m)\,dm, \qquad (1)$$

where τ_m is the lifetime of a star of mass m. The integrand in this equation gives the precursor mass distribution, discussed in § 2.3.

The sensitivity of predictions to the stellar birthrate function will be tested by considering several alternatives. The first SFR to be used is simply $\psi(t)$ = constant = ψ_1; the other SFR is a modified power law, $\psi(t) = 12.5\psi_1/(t+0.5)$, where ψ_1 is the SFR at the adopted present time t_1 = 12 Gyr, and t is in Gyr ($\equiv 10^9$ years). The value of ψ_1 is chosen to provide a present column density 75 $M_\odot$ pc^{-2} of stars (excluding mass once in stars that has been ejected); the alternative functions require respectively $\psi_1 = 8.3$ and $\psi_1 = 2.5$ $M_\odot$ pc^{-2} Gyr^{-1}. In the latter case the average past SFR is 3 times the present rate; both functions satisfy the constraints on that ratio imposed by the method of Schmidt (1959) based on the stellar luminosity function (as in Tinsley, 1977b).

Two IMF's will be considered. The first is a power law, $\phi(m) \propto m^{-(1+x)}$, with x = 1.3 for all relevant masses, 0.9 < m < 5 $M_\odot$ (Salpeter, 1955). The alternative IMF represents the solar neighborhood function in more detail, with slopes x = 1.3 for masses 2 < m < 5 $M_\odot$, x = 1.0 for 1 < m < 2 $M_\odot$, and x = 0.25 for 0.9 < m < 1 $M_\odot$. The poorly-known IMF for masses outside the range of interest is eliminated by scaling the relevant part of $\phi(m)$ to the empirical density of turnoff stars; in this way, the IMF for the turnoff mass is estimated to be $\phi_1 = 0.10$. The PN rate predictions below bear an uncertainty of perhaps a factor of 2 due to the normalization to stellar densities via $\psi_1\phi_1$.

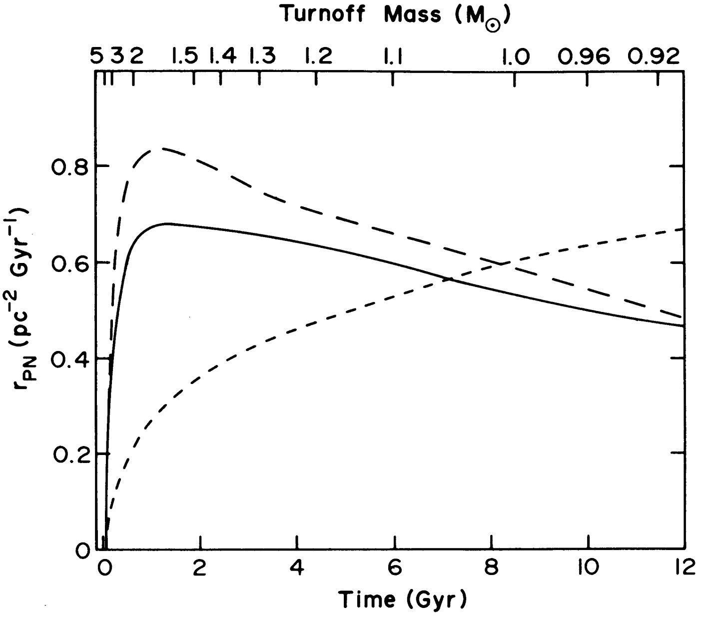

Figure 1. Rate of occurrence of PN in models for the solar neighborhood with various stellar birthrate functions: solid line: power-law IMF and decreasing SFR; long dashes: "local" IMF and decreasing SFR; short dashes: "local" IMF and constant SFR.

Calculated PN rates as a function of time are shown in Figure 1. If the SFR is constant, r_{PN} increases steadily as the contributing mass range widens, i.e. as the turnoff mass decreases (cf. lower limit to the integral in equation [1] and the upper scale in Figure 1). However, with a rapidly declining SFR the PN rate falls after an early maximum, because of the declining contribution of stars more massive than turnoff. This effect is seen to be more pronounced with the "local" IMF, because it is richer in massive stars.

It can be seen that the predicted present PN rate is insensitive to the choice of stellar birthrate function; differences among the 3 cases, at 12 Gyr, in Figure 1 are much less than the common uncertainty in normalization. This model insensitivity arises because the PN rate depends strongly on the rate at which stars just above turnoff are dying, and all cases have been scaled to the same present density of stars at turnoff. A different result would have been obtained if we had scaled to, say, the present birthrate of stars above 2 $M_\odot$, but the adopted method of normalization appears to suffer from the smallest empirical uncertainties. Consequently, the PN rate does not provide any stronger constraints on the IMF or SFR than can be derived from the densities of main sequence stars and related quantities.

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2.2 Comparison with empirical rates

Two recent papers have discussed the PN rate in the solar neighborhood, and their results can be reconciled as follows. The estimates by Alloin, Cruz-Gonzalez, and Peimbert (1976) should be increased by a factor 1.3 to allow for an incompleteness in the PN catalogue described by Cahn and Wyatt (1976); in addition, Cahn and Wyatt's values based on the distance scale of Cudworth (1974) appear to need an extra correction factor to allow for the effect of distance on the nebular radius (Alloin et al., 1976). With these adjustments, both sets of authors would obtain $r_{PN} = 1.2$ pc^{-2} Gyr^{-1} for the Cahn and Kaler (1971) distance scale, and $r_{PN} = 0.3$ pc^{-2} Gyr^{-1} for the Cudworth scale, with uncertainties $\sim$ 20% in each case.

The model predictions in Figure 1 agree with these empirical rates within the errors, although it is clear that a more critical comparison cannot yet be made. It would be rewarding to reduce the uncertainties on both sides far enough to test whether each PN precursor does eject just one PN, as assumed. A more sensitive way of using PN statistics to constrain the SFR is discussed next.

2.3 The precursor mass distribution

Figure 2 illustrates the predicted present mass distribution of PN precursors, for the models used in Figure 1. (The line labelled "Return" will be discussed in § 2.4.) Here the SFR makes a striking difference, because a decreasing function leads to a smaller contribution from the recently formed more massive precursors. The choice of IMF, paradoxically, has little effect on the mass distribution, because its slope is not subject to serious uncertainties in the mass range of interest.

According to Figure 2, a constant SFR would result in about equal numbers of PN precursors with initial masses in the three intervals 0.9 to 1.2 $M_\odot$ (mid-G to mid-F at turnoff, cf. upper scale), 1.2 to 2 $M_\odot$ (early F and A stars), and 2 to 5 $M_\odot$ (late B stars). By contrast, an SFR decreasing as sharply as the function used here would result in about 65%, 20%, and 15% of precursors in the respective intervals. Data on the Galactic distribution and kinematics of PN could perhaps discriminate between such cases. Grieg (1971) identified two classes of PN, for which Cudworth (1974) confirmed rather different kinematic properties, resembling stars of less than 1 $M_\odot$ and about 1.5 $M_\odot$ respectively. Comparable numbers of PN were listed for each class, but the completeness needs investigation, for example to see whether a substantial number of PN distributed like B stars may be undetected. Further study of this question may lead to useful constraints on the variation of the SFR with time.

This test for the time-dependence of the SFR is closely related, in principle, to Mayor and Martinet's (1977) consideration of the mass distribution of A, F, and G stars. The two approaches may prove to be

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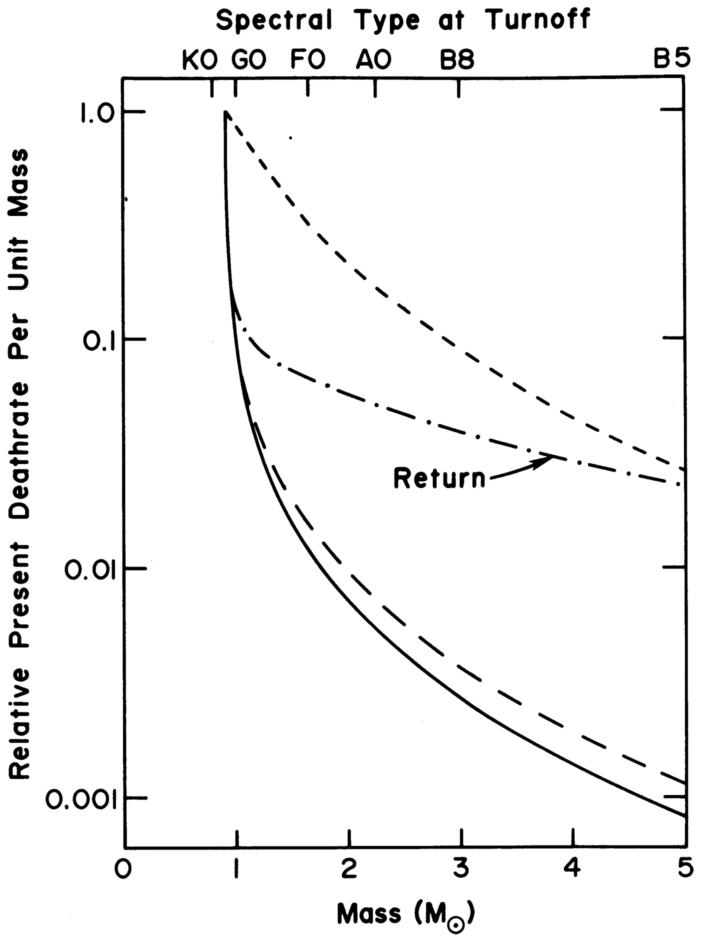

Figure 2. Three curves give the distribution of original masses of precursor stars of PN at time 12 Gyr; the models use different stellar birthrate functions, as in Figure 1. Dash-dotted line: contribution per unit mass to the rate of mass ejection (counting the whole envelope above the white dwarf) in the model with the "local" IMF and decreasing SFR. All quantities are normalized to unity at the turnoff mass.

usefully complementary in that they use independent data suffering from different biases and problems of interpretation.

2.4 The interstellar gas balance in the solar neighborhood

The total rate of mass ejection by PN precursors (including giant stars with winds) depends on the PN occurrence rate and on the original and final stellar masses. If, for example, we assume an average white dwarf mass of 0.7 $M_{\odot}$ and an average precursor mass of 1.2 $M_{\odot}$, the em-

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pirical PN rate (§ 2.2) corresponds to an ejection rate of 0.15 - 0.6 $M_\odot$ pc^{-2} Gyr^{-1}.

Models for the solar neighborhood give similar results. For example, the case with the above "local" IMF and decreasing SFR leads to a present ejection rate of 0.31 $M_\odot$ pc^{-2} Gyr^{-1}; the average loss per PN precursor is 0.7 $M_\odot$, suggesting that much of the envelope is blown off before the PN shell. The curve labelled "Return" in Figure 2 shows the relative mass loss rate as a function of (original) stellar mass; about half the total comes from stars above 2 $M_\odot$, although these contribute only 15% of the PN rate by number. A constant SFR would evidently give rise to more mass loss from the more massive precursors, resulting in a greater total mass return rate for a given PN rate.

The preceding mass return rates are now to be compared with the contribution from massive stars (presumably supernova precursors), and the overall ejection rate is to be compared with the rate at which gas is used up in star formation. The relations between these rates are, of course, crucial to chemical evolution.

Again using the "local" IMF and decreasing SFR, the predicted ejection rate from stars above the adopted PN precursor mass range is 0.26 $M_\odot$ pc^{-2} Gyr^{-1}, similar to the rate from less massive stars. This comparison is sensitive to the choice of dividing mass: if it were 8 $M_\odot$ rather than 5 $M_\odot$, two-thirds of the mass ejection would be from PN precursors (although mostly not in the PN shells themselves). Supernova rates are too uncertain to give the dividing mass precisely (Tammann, 1977, Tinsley,1977a), but the Galactic distribution of PN may be a useful approach to this quantity. Conversely, the uncertainty in the upper mass limit for PN precursors affects the interpretation of the PN distribution in terms of the SFR (§ 2.3), because of course there are relatively more B stars among PN precursors if the limit is 8 $M_\odot$ rather than 5 $M_\odot$.

The combined ejection rate from all stars is a fraction R = 0.23 of the present SFR, in the model under consideration, so the net rate of gas consumption by stellar births and deaths is $(1-R)\psi_1 = 2$ $M_\odot$ pc^{-2} Gyr^{-1}. Given the uncertainties in all the factors entering this estimate, the so-called "net SFR" could plausibly lie anywhere in the range $\sim$ 0.8 to 10 $M_\odot$ pc^{-2} Gyr^{-1}.

Now the relevant timescale for changes in chemical abundances in the interstellar gas is the ratio of gas content to net gas consumption rate. For a local gas density of 6 - 9 $M_\odot$ pc^{-2} (Gordon and Burton, 1976), and the foregoing net SFR, this timescale could be as long as 10 Gyr or as short as 0.5 Gyr. A further complication is that gas infall into the solar neighborhood could be as fast as 2 $M_\odot$ pc^{-2} Gyr^{-1} (Oort, 1970; Cox and Smith, 1976), which may cancel the gas consumption rate due to stellar births and deaths. Such an influx would profoundly affect chemical evolution, making rates of change of chemical abundances very slow indeed (Larson, 1972; Audouze and Tinsley, 1975).

In summary, it is unlikely that mass loss from PN precursor stars is itself a major factor in the interstellar gas balance in the solar neighborhood, but PN statistics may provide checks on many parameters relevant to chemical evolution.

3. CHEMICAL ENRICHMENT BY PLANETARY NEBULAE

3.1 Preliminary estimates: the yield

PN undoubtedly contribute to the long-term enrichment of the Galaxy in elements that are overabundant in the nebulae. The important question is whether PN contribute a significant fraction of the interstellar abundance level of any element.

An order-of-magnitude estimate of the interstellar abundance arising from a given source of an element is the quantity called its yield. For an element contributed by PN, the yield is defined as the ratio (ejection rate via PN of element synthesized in precursor stars)/(net SFR); i.e.,

$$y \equiv [X(PN) - X(ISM)]m_{PN}r_{PN}/(1-R)\psi, \qquad (2)$$

where X(PN)-X(ISM) is the excess abundance in PN over the interstellar value, m_{PN} is the nebular mass, r_{PN} is the rate by number, and $(1-R)\psi$ is the net SFR. Being based on the rate ratio $m_{PN}r_{PN}/\psi$, the yield is much less vulnerable to model-dependent effects than are estimates based on the present ejection rate multiplied by the age of the Galaxy. Depending on poorly-evaluated processes such as infall or variations in the IMF, the contribution of PN to the abundance of an element may be in the range $\sim$ y to 3y (cf. Audouze and Tinsley 1975). A condition for PN to contribute most of the abundance X(ISM) of an element is thus $y \gtrsim X(ISM)/2$, i.e.,

$$\frac{X(PN)}{X(ISM)} - 1 \gtrsim \frac{(1-R)\psi}{2m_{PN}r_{PN}}. \qquad (3)$$

For example, given the estimates $m_{PN} = 0.3\ M_{\odot}$, $r_{PN} = 0.5\ pc^{-2}Gyr^{-1}$, R = 0.23, and $\psi_1 = 2.5\ M_{\odot}\ pc^{-2}\ Gyr^{-1}$, we find that an overabundance X(PN)/X(ISM) > 7 would implicate PN precursors as the main source of the element considered. (Because of the uncertainties in equation [3] and in the quantities on the right-hand-side, much smaller overabundances than the nominal value of 7 may be significant.) Reported overabundances by factors up to $\sim$ 10 (see Peimbert's review in these Proceedings) point to a very important role for PN in chemical enrichment.

The overall contribution of PN precursor stars to the enrichment must be greater than indicated by the yield based on nebular masses and compositions, since the previously ejected envelopes must share some of the same abundance enhancements as the nebulae. In particular, the relative overabundances (e.g. of carbon with respect to nitrogen) could be distorted if only the PN themselves are considered. Caution is thus needed in using PN to evaluate chemical enrichment by low-mass stars.

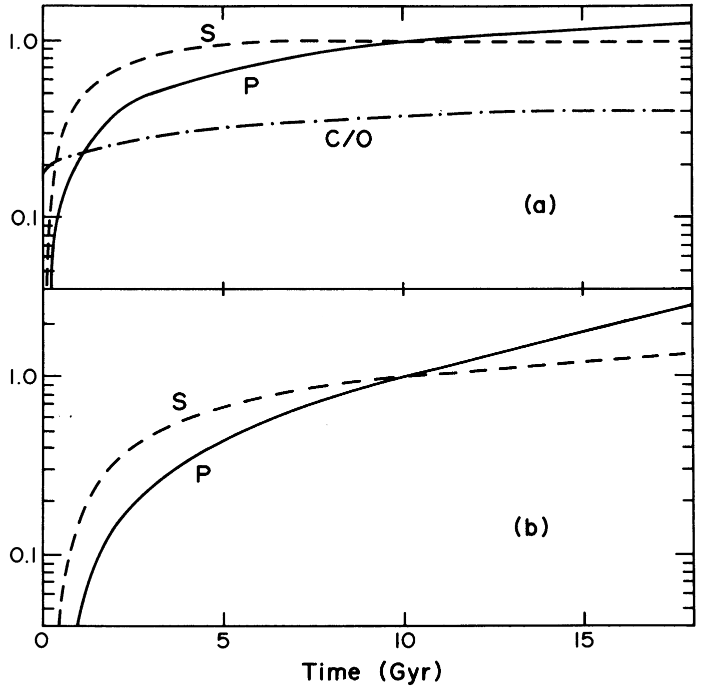

Figure 3. Abundance ratios, relative to their values at 10 Gyr, in two consistent models for chemical evolution in the solar neighborhood: (a) a model with infall (model 1 of Tinsley [1977b]), (b) a model with finite initial abundances of elements from massive stars (model 3 ibid.). Solid lines (P) show the abundance ratio of primary elements made in low-mass stars (< 5 $M_\odot$) to primary elements made in massive stars. Dashed lines (S) show the corresponding ratio for secondary elements. Dash-dotted line: the $^{12}C/^{16}O$ ratio (by mass) calculated under assumptions described in the text.

3.2 Time-dependence

The yield of any element due to PN and their precursors increases with time since the ratio r_{PN}/ψ does so (eqs. 1, 2). By contrast, yields due to massive stars are constant because the stellar death- and birthrates are essentially equal. Thus the abundances of elements from PN tend to grow relative to those from supernovae, and the former elements should be relatively underabundant in the oldest stars.

Possibilities may be illustrated by some schematic calculations of the relative interstellar abundances of putative elements synthesized exclusively in less and more massive stars respectively (with the division at 5 $M_\odot$). Figure 3 shows such abundance ratios for both primary and secondary elements, in two models that are consistent with data on the SFR, stellar metallicity distribution, etc., in the solar neighbor-

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hood. In most cases, differences from the present ratios exceed the observational scatter in stellar abundances only in the oldest stars, so it will take accurate data on the abundances and ages of many stars to reveal such effects.

A pair of elements to consider as an example is ^{12}C and ^{16}O. Since not all ^{12}C is thought to come from PN precursors, these elements cannot be identified with the primary pairs in Figure 3. To be more realistic, the curve "C/O" includes the yields of C and O from massive stars given by Talbot and Arnett (see Fig. 2 of Audouze and Tinsley [1975]), as well as additional ^{12}C assumed to be mixed out from the cores of stars in the PN precursor mass range; partial burning of ^{12}C to ^{13}C and ^{14}N in stellar envelopes has been included (as calculated by Dearborn [1977]). The massive stars alone would give too little C relative to O by a factor of 2. Thus the amount of core carbon from low-mass stars has been chosen <u>ad hoc</u> to provide about the solar C/O ratio in the interstellar medium at the sun's formation time; the requirement is 0.0064 $M_\odot$ of carbon per low-mass star. Remarkably, if this extra carbon were contained in a PN shell of mass 0.2 $M_\odot$ it would give just the factor of 9 overabundance reported by Torres-Peimbert and Peimbert (1977). Of course there are uncertainties arising from the galactic model, other aspects of nucleosynthesis, etc., so these results are only suggestive. A reasonable conclusion is that the solar C/O ratio and estimates of nucleosynthesis in massive stars are together <u>consistent</u> with a major additional source of carbon arising from PN precursors, as indicated by the nebular overabundances.

The case of nitrogen is more complicated, partly because its secondary nature may lead to time-dependent abundance ratios whatever the mass of its source stars (see the review of CNO nucleosynthesis by Truran [1977]). Suffice it to note that PN apparently represent a significant source of nitrogen, according to the criteria of § 3.1.

4. POPULATION II PLANETARIES AND GALACTIC EVOLUTION

4.1 Prediction

In stellar populations that were formed in essentially one initial burst, the PN rate can be predicted from the IMF and stellar lifetimes (Cahn and Wyatt, 1976). It is convenient to eliminate the unkown amount of mass in stars below turnoff by normalizing to the luminosity, which is largely due to giant stars that are the immediate precursors of PN. Since the giant lifetime (τ_g) of a turnoff star is much less than its total lifetime, the number of giants is approximately τ_g times the stellar deathrate, which will be denoted r_{PN} on the usual assumption that each star ejects one PN. Now let ℓ_g be the average luminosity (in a chosen wavelength interval) of a giant, defined so that $\ell_g \tau_g$ is the integrated light output during giant evolution; and let G be the fraction of luminosity of the system that comes from giant stars. The total luminosity is thus $L = \ell_g \tau_g r_{PN}/G$. Let τ_{PN} be the visible life-

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time of a PN, so their number is $N_{PN} = \tau_{PN} r_{PN}$. Finally, the number of PN per unit luminosity is given by

$$N_{PN}/L = G\tau_{PN}/\ell_g \tau_g . \qquad (4)$$

This quantity can be converted to Alloin et al.'s (1976) "specific PN rate" via the mass-to-luminosity ratio, but often that factor adds unnecessary uncertainty.

4.2 Globular clusters

A prediction of the number of PN in Galactic globular clusters may be made from an estimated total blue luminosity, $L \simeq 200 \times 10^5\ L_\odot$, with $G \simeq 0.5$ and $\ell_g \tau_g \simeq 5 \times 10^{10}\ L_\odot$ (based on their stellar populations). With $\tau_{PN} = 20{,}000$ yr, equation (4) predicts $N_{PN} \sim 4$. The observed number of one is well within the astrophysical and statistical uncertainties of the prediction, but the uncertainties preclude a strong test of the assumption that each dying globular cluster star makes one PN. Alloin et al. (1976) note that the efficiency could be smaller, because of the very small mass of the nebula in M15; Population II stars probably have little mass to lose, in either a wind or a PN shell, since their turnoff mass is close to the white dwarf mass. For the next application of equation (4), it is useful even to conclude that the PN rate for globular cluster stars is within an order of magnitude of their deathrate.

4.3 The halo

Scaling from one PN in the globular cluster system of total mass $\sim 2 \times 10^7\ M_\odot$ to about 100 PN in the halo population (Cahn and Wyatt, 1976), we can estimate that the halo contains a mass $\sim 2 \times 10^9\ M_\odot$ of cluster type stars. This would be an underestimate of the total halo mass if the field Population II has relatively more stars below turnoff than the clusters. The low estimate is consistent with that derived by Schmidt (1975) from counts of subdwarfs, which showed no evidence for a rapidly increasing population of even less massive stars. Cahn and Wyatt (1976) also concluded from PN statistics that the halo is not very massive.

Alloin et al. (1976) adopted the orders-of-magnitude larger halo masses that have been suggested on dynamical grounds (Ostriker and Peebles, 1973), and concluded that only a very small fraction of extreme Population II stars become PN. Because a very low efficiency of PN production is excluded by the globular cluster data (§ 4.2), this argument requires most of the halo to be in objects that do not affect chemical evolution by their mass loss.

Effects of mass loss by halo stars on evolution of the disk have been studied by Ostriker and Thuan (1975). From PN statistics similar to the above, those authors concluded that altogether $\sim 1/8$ of the disk mass could be matter shed in the past by halo stars. Most of this contribution to infall would have been at early times; the 100 estimated PN in the present halo population contribute negligibly to the overall gas balance of the Galaxy. Even if the mass lost by each precursor is as large as 0.3 $M_\odot$, the total ejection rate is only 0.1% of the Galactic star formation rate of a few solar masses per year.

In conclusion, research on planetary nebulae can make an important contribution to the field of galactic evolution, both in constraining such key factors as the past rate of star formation, and in providing information on chemical enrichment by stars of low mass. It will be valuable to acquire further data on the compositions, distribution, and kinematics of PN, and on the compositions and original masses of their precursor stars.

This research was supported in part by the National Science Foundation (Grant AST76-16329) and by the Alfred P. Sloan Foundation.

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DISCUSSION

Aller: The rate of enrichment of the interstellar medium in heavy elements depends on the mass of precursor star and depth from which processed material can be fed into the interstellar medium. Planetaries associated with stars showing H absorption lines don't tend to show conspicuous nitrogen excess while those with Wolf-Rayet type and purely continuous spectra do. UV observations are needed to securely fix the C abundance. Quantitative predictions of enhancement rates would be extremely difficult.

Tinsley: I think it would be very useful to see if there is any pattern in the abundances of planetaries compared to their population type, in other words, the masses of the precursors.

Ford: I would like to remark that there are planetary nebulae in three elliptical galaxies which have population II stars, namely Fornax, NGC 147, and NGC 185. Population II stars can and do produce planetary nebulae.

Tinsley: The same is true in the halo in this galaxy. If you wanted to have a very massive halo of evolving stars, then you would have to say that they were much less efficient in making planetaries than the globular clusters. You might be allowed a factor of 4 or 5 more, just because one in a globular cluster is not good statistics.

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