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STELLAR MASS AND THE EVOLUTION OF PLANETARY NEBULAE

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ABSTRACT

The temperatures of the central stars of planetary nebulae show a strong dependence on the radial velocities of the nebulae. High-temperature nuclei are confined to $|V_r(\text{LSR})| \lesssim 80$ km s^{-1}, whereas nebulae with $|V_r(\text{LSR})| \gtrsim 80$ km s^{-1} are low-excitation objects. A confirming, although much weaker, effect is seen with respect to distance from the galactic plane; low $|Z|$ nebulae tend toward higher excitation. The low-velocity stars, which are associated with the galactic disk, can have higher initial mass than can those stars of high velocity, which belong as a class to the halo, and can have higher mass on the asymptotic giant branch before the ejection of the planetary. The results presented here then show that higher mass leads to higher maximum effective temperature of the planetary nucleus, in agreement with theory. It is also clear on empirical grounds alone that a single evolutionary track cannot be established for planetary nuclei, and that a family of tracks for stars of different mass must be used. The maximum temperatures observed for the halo stars indicate that planetary nuclei and the resulting halo white dwarfs now being formed have masses of about 0.5 $M_\odot$, implying that these stars have lost nearly half their initial mass. Other theoretical constraints suggest that the halo nebulae have low masses, less than or equal to about 0.1 $M_\odot$, which in turn suggests that their distances are currently overestimated. This nebular mass agrees with Webster's assessment of the mean masses of galactic bulge planetaries.

Subject headings: nebulae: planetary — stars: evolution

I. INTRODUCTION

The planetary nebulae and their central stars represent the transition between stars on the asymptotic giant branch and the white dwarfs. These highly visible objects can be used both to explore the later evolutionary stages of stars and to examine properties of the Galaxy. Many attempts have been made to follow the evolution of stars during their planetary nebula stage. There are two approaches to this study, the empirical and the theoretical, and a prime object is to demonstrate agreement between the two. Harman and Seaton (1964) and Seaton (1966) developed what has been for many years the standard empirical evolutionary track. As an example of the theoretical, Paczyński (1971) computed evolutionary tracks as a function of stellar mass. The theoretical curves by and large pass through the neighborhood of the observed points, but the fit with the above empirical track is not good. One major problem has been the inability to discriminate different stellar masses in the empirical studies. Recently, however, Renzini (1978) has shown that a more reasonable fit between the theoretical curves and the observations can be made if the lifetimes of the stars of different masses on the various portions of their Paczyński tracks are taken into account.

The establishment of the empirical H-R diagram for the planetary nuclei, and the resulting test of theory, is beset with two severe difficulties. The first involves the measurement of the temperature of the central star, T_*. This quantity is usually determined by applying the Zanstra method (see Harman and Seaton 1964), which in its various forms is valid over the entire temperature range, or by the Stoy method (Kaler 1976*a*) which is valid for the cooler stars. However, Pottasch *et al.* (1978) have shown that the He II Zanstra method used for the hotter stars can severely overestimate T_*, and that for some nebulae an accurate value can be determined only by going to far-ultraviolet observations by satellite. Heap (1977) and Aller (1977) also point out that high He II Zanstra temperatures are sometimes not consistent with the temperatures indicated by the visual stellar spectra, which might also indicate an ultraviolet excess. As of now, the amount of ultraviolet data are severely limited, and the discrepancy between the ultraviolet and the Zanstra temperatures is not yet resolved.

The second problem is that of the distances to the nebulae, which enter strongly into the calculation of the luminosities of the stars (as do the temperatures). Distances to the larger, optically thin nebulae (with generally hotter stars) are usually computed on the assumption that all nebulae have the same mass (see, for example, Seaton 1966). However, planetaries are produced by stars of widely varying masses, and since it would seem reasonable that the mass of the planetary shell depends upon stellar mass, this distance system contains serious errors. There is also some good empirical evidence for this supposition: Seaton (1966, 1968) shows that the average mass of the planetaries is between about 0.2 $M_{\odot}$ and 0.4 $M_{\odot}$, where Peimbert (1973) shows that the planetary in M15 has a mass of only about 0.02 $M_{\odot}$. Additional proof is indicated later in this paper. The distances to the smaller, optically thick nebulae, which have the cooler central stars, are even more poorly known. The usual method is to assume that these nebulae all have the same intrinsic luminosity (see, for example, Cudworth 1974). This assumption precludes placement of these stars on the H-R diagram.

It is the purpose of this paper to provide evidence on the stellar and nebular masses in the planetary nebulae regime of the H-R diagram. This evidence will be developed by examining quantities related to the stars' temperatures only, thus avoiding any dependence on the distances to the nebulae.

II. GALACTIC DISTRIBUTION OF STELLAR TEMPERATURES

Ideally, we would like to have available true effective temperatures of planetary nuclei. Good values seem to be available for stars of low-excitation nebulae (Kaler 1976*a*) which have weak or absent He II lines. But because of the problems discussed in the last section, effective temperatures for nuclei of high-excitation nebulae are difficult to produce. The problem is that the He II Zanstra method samples the star for $\lambda < 228$ Å, where there is apparently an excess of radiation for some stars. In addition, accurate magnitudes of the central stars must be available, a fact which limits the number of nebulae that can be examined. Instead of temperature for these objects, we can make use of a nebular excitation parameter, Ex $= \mathrm{He}^{2+}/\mathrm{He}$, which should bear a strong relation to the temperature. All other things being equal, Ex will be in some way proportional to T_*. Kaler (1978*a*) made use of this parameter in the construction of ionization curves.

In this examination of stellar temperatures, log T_* is used for nebulae with weak or absent He II lines. Values are directly measured by the Stoy method or calculated from the $I(\lambda 5007)$[O III]$/I(\mathrm{H}\beta)$ ratio (Kaler 1978*b*). The Ex scale for high-temperature stars is joined to this temperature scale such that Ex = 0 at log $T_* = 4.75$. There are two classes of nebulae for which Ex is calculated. In the first, accurate He/H ratios are known, and values of Ex are taken from Kaler (1978*c*, 1979, 1980). In the second class, only $\mathrm{He}^{2+}/\mathrm{H}^+$ from λ4686 He II is available. Ex is then set equal to $10(\mathrm{He}^{2+}/\mathrm{H}^+)$, where it is assumed that He/H = 0.1. Since planetaries commonly have He/H > 0.1 (see Kaler 1978*c*), Ex for this category will often be somewhat overestimated. Data for $I(\lambda 4686)$ were taken from Kaler (1976*b*), from the list of additional references cited in Kaler (1978*c*, 1979), and from unpublished observations made at the University of Illinois Prairie Observatory. This second class of nebulae is used primarily for confirmation purposes.

In Figure 1 (log T_*, Ex) is plotted against the absolute value of the radial velocity of the nebula with respect to the local standard of rest, $|V_r(\mathrm{LSR})|$, where basic solar motion is adopted (see Mihalas and Routly 1968). Heliocentric radial velocities were taken from Perek and Kohoutek (1967), Bohuski and Smith (1974), and Acker (1975). The closed circles represent the 91 nebulae for which accurate He/H ratios are available. The open circles show the additional 80 objects in the second class. For log $T_* < 4.8$ the open circles are accurately placed, but as $\mathrm{He}^{2+}/\mathrm{H}^+$ increases, the size of the possible error increases. If we concentrate first on the filled circles, the figure shows a cutoff in the high-excitation nebulae at $|V_r(\mathrm{LSR})| \approx 80$ km s^{-1}. This figure is similar to the classical dividing line between Populations I and II. High-velocity nebulae show only low excitation. The open circles (for which only $\mathrm{He}^{2+}/\mathrm{H}^+$ is known) show a larger scatter, as expected, but nevertheless confirm this result. This

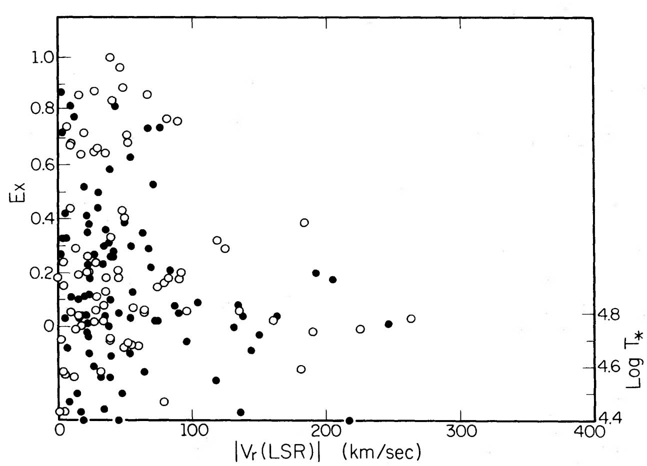

FIG. 1.—(Log T_*, Ex) for planetary nebulae, plotted against the absolute radial velocity with respect to the local standard of rest, $|V_r(\mathrm{LSR})|$. The filled circles represent reliable measures of Ex $= \mathrm{He}^{2+}/\mathrm{H}^+$ for which the He I line intensities have been measured. The He I intensities for the open circles have not been measured, and it is assumed that He/H = 0.1. The open circles plotted with Ex will be upper limits if He/H is enriched above 0.1.

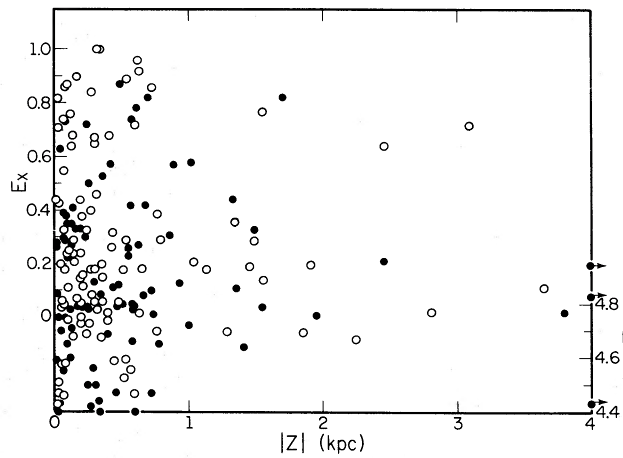

FIG. 2.—(Log T_*, Ex) for planetary nebulae, plotted against absolute distance from the galactic plane, $|Z|$. See Fig. 1 for an explanation of the symbols.

distribution of points is highly significant. Divide the nebulae with accurate values into two groups at $|V_r(\mathrm{LSR})| = 80$ km s^{-1}. From the distribution of nebulae with $|V_r(\mathrm{LSR})| < 80$ km s^{-1}, we expect seven of the 17 of the high velocity group to have Ex > 0.25; there are none. If all points are used, we expect 13 of the 32 high-velocity nebulae to have Ex > 0.25; there are only 5. From a χ^2 test, the probability that this distribution of the closed points is due to chance is less than 0.001; the same probability for all the points is only 0.007. The correlation is reminiscent of that found by Johnson (1954) between [O III] strength and radial velocity.

A similar, although much weaker, effect is seen when (log T_*, Ex) is plotted against absolute distance from the galactic plane, $|Z|$, in Figure 2. The distances of the optically thin nebulae (generally those with Ex > 0) are taken from an updated version of Cahn and Kaler (1971) by Cahn (private communication), and those of the thick (Ex < 0) nebulae are computed on Cudworth's (1974) scheme, but divided by 1.45 in order to provide a consistent scale. The difference in distribution of the filled circles above and below 1 kpc is not significant. However, in this case, both classes of nebulae can be used in order to provide a larger number of data points. Here the open circles have more significance, since three of them with $|Z| > 1$ kpc are so high that they cannot be brought down into the lower excitation range. On the basis of all the nebulae with $|Z| < 1$ kpc, we expect 12 nebulae with Ex > 0.25 and $|Z| \geq 1$ kpc; there are nine. From those objects with $|Z| < 2$ kpc, we expect four with Ex > 0.25 and $|Z| > 2$ kpc; there are two. By itself the correlation with $|Z|$ is not very significant; a χ^2 test shows that the chance probability of the distribution for $|Z| \geq 1$ kpc is 0.29. However it does tend to confirm and support the relation found in Figure 1 for $|V_r(\mathrm{LSR})|$, that is, that Population II (halo) objects have nuclei of lower maximum effective temperature.

In fact, we would not expect the $|Z|$-relation to be as strong as the $|V_r(\mathrm{LSR})|$-relation, since the distances to individual planetaries are afflicted with errors, as pointed out in § I. Furthermore, since the planetaries in the disk can be generated by stars more massive than those found in the halo, the dispersion of nebular masses in the disk will be different from that in the halo, and there will be systematic differences in the calculation of $|Z|$ between halo and disk objects. This point will be expanded further in § III. In addition, it is possible that some of the nebulae with high $|Z|$ and high Ex are optically thick, in which case $|Z|$ would be overestimated. Given the above problems, the Z-distribution will not be discussed further, and the nebulae with $|V_r(\mathrm{LSR})|$ greater or less than 80 km s^{-1} will be called "halo nebulae" and "disk nebulae," respectively, even though the computed distances place some of the disk nebulae within the confines of the halo and vice versa. The effect of observational selection is not known. Clearly more observations, particularly toward the galactic center, are needed.

III. CONCLUSIONS

A number of interesting conclusions can be drawn from Figure 1. First, note that the distribution of points (especially that of the accurately placed filled circles) shows an apparent sudden cutoff at 80 km s^{-1}, as mentioned in § II, which indicates that we are dealing with two distinct populations and not a continuous distribution.

Second, since halo planetary nuclei do not get as hot as the disk objects, they clearly will have different paths on the H-R diagram. The low-velocity, or disk, objects will as a class contain progenitor stars which range to higher mass than will those of the halo. It is thus here evident on empirical grounds alone (as has been known theoretically for some time) that a single evolutionary track will not suffice and that nuclei of different masses will have different evolutionary tracks. The higher mass stars will have tracks shifted to the left (higher temperature), qualitatively in accord with, for example, Paczyński's (1971) theoretical tracks, and Renzini's (1978) positioning of observed objects on the H-R diagram.

Third, these results provide evidence on the masses of both the stellar and nebular components of halo planetary nebulae. This work is preliminary in the sense that Ex, and not T_*, is used for high-temperature stars. The calculation of T_* presents difficulties, as pointed out in § I. In addition the central stars of many of the nebulae studied here do not have measured magnitudes. However, enough values of T_* have been calculated (Kaler, unpublished) so that an approximate relation between Ex and a maximum T_* for that value of Ex can be established. This relation is confused, however, by the large low-surface brightness nebulae such as NGC 3587 and NGC 6720 which have high T_* but low Ex, probably because of the low luminosity of the star. According to Renzini's (1978) theory, these objects are produced by high-mass stars which would only be found in the disk. And, in agreement with theory, that is in fact where they are found. Thus these anomalous objects can be excluded from the relation between Ex and maximum T_*, which then becomes more well defined. From this relation, Ex = 0.2 (the maximum halo value of Ex from the filled circles of Fig. 1) corresponds to a maximum T_* of 95,000 K ± 5000 K. (It is well known that T_* can well exceed 10^5 K in the disk—see Harman and Seaton 1965). It is assumed that for these objects the He II Zanstra temperatures are correct. However, if some, or even all, of them are overestimates (see § I) of the true effective temperatures, this maximum T_* for a given Ex is obviously still valid. From Paczyński's (1971) evolutionary tracks, we can define a relation between the left-most (highest T_*) penetration of an evolutionary track and the mass of the remnant star. This relation is not dependent upon population type through the metal abundance. Gingold (1974) calculated an evolutionary track for a 0.6 $M_\odot$ star of low metal abundance which has very nearly the same leftward penetration as the Population I Paczyński (1971) track. From an extrapolation of the above relation, a maximum T_* of 95,000 K ± 5000 K corresponds to a mass of 0.5 ± 0.02 $M_\odot$. The mass so derived is quite insensitive to the value of maximum T_*. (If we use all the points, and Ex = 0.3, the resulting mass is 0.52 $M_\odot$.) Thus the halo nuclei and the resulting crop of white dwarfs have masses of about one half of a solar mass. The minimum initial mass of a star that has evolved in the lifetime of the halo is thought to be about 0.8 $M_\odot$, although the minimum mass of a star which will produce a planetary may well be larger than 0.8 $M_\odot$. The likely conclusion then is that these stars must lose at least 40% of their initial masses before becoming white dwarfs.

The mass derived above is consistent with masses of evolved halo stars derived from other methods. Christy (1966) found from pulsation theory that RR Lyrae stars should have masses of 0.5 $M_\odot$. Iben and Rood (1970) showed from evolutionary considerations that stars on the horizontal branches (HB) of globular clusters should have masses between 0.56 and 0.76 $M_\odot$. Philip and Hays (private communication) find a similar value of 0.62 ± 0.2 $M_\odot$ for these stars; see Hays and Philip (1979). A study of Population II Cepheids by Böhm-Vitense *et al.* (1974) indicated masses of 0.55 ± 0.05 $M_\odot$ for these stars. From these figures, the masses of Population II stars prior to ejection of a planetary are about 0.6 (+0.15; −0.1) $M_\odot$.

The true error in the above mass and in that for the currently forming halo white dwarfs derived here is not known. If we take the numbers at face value, however, some further interesting conclusions can be drawn. If we assume that the above HB stars and Cepheids will become the kind of planetary nuclei discussed here, they must lose an additional 0.1 (+0.15; −0.1) $M_\odot$. Since they will probably lose some mass in climbing the asymptotic giant branch before the planetary is ejected, the mass of the resulting nebula will be less than or equal to 0.1 (+0.15; −0.1) $M_\odot$.

The average mass of all planetaries is usually taken as between 0.17 $M_\odot$ and 0.38 $M_\odot$, for an adopted filling factor, ϵ, of 0.63, depending upon whether the smaller or larger distance scale is adopted (Seaton 1966, 1968). The smaller is the one used by Cahn and Kaler (1971), and the larger is the same as that derived independently by Cudworth (1974). The masses (with the error) of the halo planetary nebulae overlap with that of the smaller scale, but the larger of the two is clearly excluded. The "average mass" involves primarily disk objects which clearly can result from higher mass stars. Thus there is a good indication that the halo nebulae have masses that are lower than their disk counterparts, and that low-mass stars produce low-mass nebulae. The mean mass of halo nebulae derived here agrees well with that found for galactic bulge objects by Webster (1976). She derived $M/\epsilon = 0.16$, which for $\epsilon = 0.63$ yields $M = 0.10\ M_\odot$. It is also consistent with the mass of 0.02 $M_\odot$ found for Ps-1 in M15 by Peimbert (1973).

If the masses of halo planetaries are only 0.1 $M_\odot$, then distances based on the constant-mass method have been overestimated providing also that the other parameters, notably the filling factor, is constant among all nebulae; see the above distance references. [This suggestion is countered by Cudworth (1974) who finds the same larger distance scale for Greig's (1971) C-nebulae, which presumably are Population II.] Since distance goes as $M(\text{nebula})^{0.4}$, the smaller distance scale will overestimate by $(0.18/0.1)^{0.4}$ or about 25%, and the larger by $(0.36/0.1)^{0.4}$ or about 65%. For optically thin halo (and bulge) nebulae, the distances given by Cahn and Kaler (1971) should probably be adopted, and even these may be overestimates.

IV. SUMMARY

The galactic distribution of the temperatures of planetary nebula central stars shows that the lower mass halo nuclei reach lower maximum temperatures than do the higher mass nuclei of the disk. This result demonstrates on independent empirical grounds that stars of different mass follow different evolutionary tracks through this region of the H-R diagram. It is in agreement with the theoretical evolutionary tracks of Paczyński (1971) and the theoretical placement of planetary nuclei on the H-R diagram by Renzini (1978).

From a comparison of the maximum stellar temperature found in the halo with theoretical evolutionary tracks, it is also evident that stars in the neighborhood of one solar mass lose a total of nearly half of that mass before finally becoming white dwarfs, and that the halo white dwarfs now being formed should have masses of about 0.5 $M_{\odot}$. A comparison of the masses of planetary nuclei with the computed masses of Population II Cepheids and horizontal branch stars implies that the halo planetary nebulae should have low masses, of the order of 0.1 $M_{\odot}$, which is in agreement with the mean mass found by Webster (1976) for galactic bulge nebulae. This nebular mass in turn suggests that the distances to optically thin halo planetaries have in the past been overestimated.

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