NUCLEI OF PLANETARY NEBULAE

C. R. O'DELL

George C. Marshall Space Flight Center, National Aeronautics and Space Administration, Ala., U.S.A.

Abstract. The nuclei of planetary nebulae are examined both observationally and theoretically. It is seen that the region occupied by these stars in the $\log T - \log L$ diagram is quite wide but consistent with a general progression of stars from high to low luminosity, with a noticeable but not large increase in luminosity during the early phase. The 'evolutionary path' is intrinsically quite wide and may indicate the evolution of stars under different conditions or non-monotonic passage along the mean path. Among the several theoretical approaches to this subject, only the double shell burning models seem to offer enough luminosity and short enough timescales to match the observations.

1. Introduction

The planetary nebulae present a unique opportunity for the study of the late stages of stellar evolution. They obviously represent a very late stage and are probably the immediate precursors of many, if not most, of the white dwarfs. The changes that occur involve most of the star, hence the timescales are not so short as to preclude their study – and, through the presence of the surrounding gas shell, they can be traced through an evolutionary sequence without seeing large changes in any one single star.

This field was given its modern beginning with the work of Shklovsky (1956) with his synthesis of the observational facts and their possible interpretation. Since that time, the observations have been markedly improved and have been subjected to progressive interpretation by many investigators (O'Dell, 1963; Seaton, 1966). At the same time, an even greater effort has been expended on theoretical understanding of the stars and their immediate precursors (Salpeter, 1971).

The presence of the nebular shell around the central stars of planetary nebulae provides the opportunity for their study that far exceeds that of other advanced states of stellar evolution. First, the extended image and its emission line spectrum cause the nebula to be detected with relative ease and, in fact, there are now more than 10^3 nebulae known (Perek and Kohoutek, 1967). Since the nuclei are very hot, they are relatively faint in the visual region; however, the gas absorbs much of the strong ultraviolet radiation from the stars and converts it to visual nebular emission.

Since most of the nebulae are optically thin, observations with slit spectrographs see both sides of the expanding shell, allowing accurate determinations of the expansion velocity and the system radial velocity (Wilson, 1950). The long standing issue of whether the motion was expansion or contraction has finally been resolved in favor of expansion by means of long time interval imaging that has detected the increase in angular size of several nebulae (Liller and Liller, 1968). When this expansion velocity is combined with the size of the nebula, it yields the characteristic time since the shell began expanding. There is no reason to doubt that the larger nebulae are simply more advanced states of the small nebula.

The highest surface brightness nebulae are clearly optically thick to hydrogen

Tayler (ed.), Late Stages of Stellar Evolution, 213–219.

https://doi.org/10.1017/S0074180900018209 Published online by Cambridge University Press

Lyman continuum radiation. This means that the brightness of the visual hydrogen recombination lines can serve as a count of ultraviolet photons. Combining this with the visual brightness of the central star gives a very wide wavelength base color-index from which the stellar temperature can be determined. Originated by Zanstra (1926), this method has been extended by Harman and Seaton (1966) to include the helium lines. As the nebula expands, the optical depth will decrease, making derived temperatures and luminosities only lower limits. However, if the stellar luminosity decreases rapidly enough, the nebula may again only become partially ionized and hence an accurate temperature indicator.

Since there are no stars close enough to allow trigonometric parallaxes, again the nebula must be used if one is to obtain accurate distances. Although bothersome assumptions must be made, allowing large individual errors, the average luminosities are probably known to a factor of two (O'Dell 1962).

In summary, we can say that it has been the nebula itself that has provided the major information for the study of the stars and it is therefore understandable why their significance did not become apparent until the nebulae themselves were thoroughly studied.

2. The Observed Evolution

The best way of illustrating the current observational picture of the central stars is by way of a plot of bolometric luminosity and temperature. Shown in Figure 1 is a plot used in 1967 at the Tatraska Lomnica Symposium (O'Dell 1968). Although some details have changed, the general picture remains the same. Basically this plot puts together all of the reliable data, using the best temperature method applicable and distances derived astrophysically or by independent means (Magellanic Clouds and M15). The probable error bars reflect the uncertainty in the calibrations, the atmospheric models used (blackbodies) and the probable errors of the parameters used. The gap at about $\log(L/L_{\odot})=3.3$ and $\log T_{\text{star}}=5.1$ is artificial. Certainly stars lie in this region, but there is not a method that gives accurate temperatures since the nebulae are optically thin at this point. The lower limits that are derived for the optically thin nebulae indicate that this region is occupied.

There are systematic differences in the nebulae surrounding stars found in various parts of this diagram. The higher luminosity stars have smaller, higher surface brightness surrounding shells, although the shell velocities are similar. In addition, the spectra of the central stars vary, with the Wolf-Rayet type occurring at the high luminosities along with other strong line spectral types, while the low luminosity stars are hotter and more often continuous in their emission.

The most direct interpretation is that the central stars change in luminosity and temperature on a timescale of about 30000 years, that being about the time required for the nebulae to expand from the small to larger sizes. This is certainly a dramatic change, for it implies a change of stellar radius of a factor of 40 over this same time period. The smallest nebulae at the top are about 0.05 pc radius while the largest are near the bottom at about 0.5 pc.

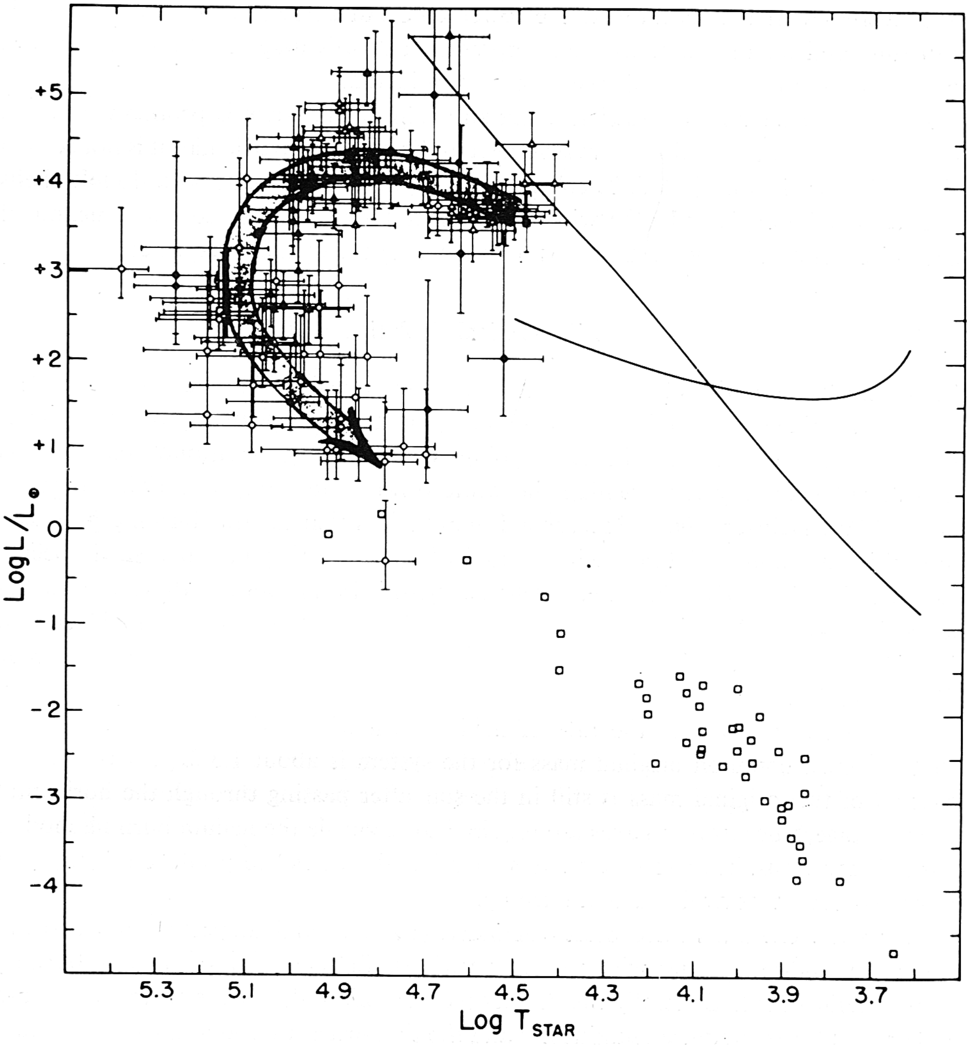

Fig. 1. The composite luminosity-temperature diagram for the nuclei of planetary nebulae and white dwarfs. Open triangles are nuclei in the Magellanic Clouds; filled triangles are optically thin objects with He II Zanstra temperatures; filled circles are optically thick nebulae; open circles are marginally optically thick; and the filled square is K648 in M15. The most probable average evolutionary path is shown superimposed on the basic data. The thin lines represent the initial main sequence and the horizontal branch.

The earliest stage of appearance is probably at about a factor of 3 lower than the peak luminosity and the stars first increase in luminosity while heating up, then monotonically decrease in brightness and then in temperature, finally blending in with the observed white dwarfs. Theoreticians have often mistakenly seized upon the early results of Harman and Seaton, indicating a very large and rapid rise in luminosity. The most complete data show that the average path is flatter at the onset

https://doi.org/10.1017/S0074180900018209 Published online by Cambridge University Press

and decreases in temperature at the lower end. An average evolutionary path is superimposed on Figure 1. In the interpretation of this diagram, both the average path and the obvious dispersion should be considered.

Although this smooth variation along an evolutionary track is probably accurate on the average, the issue does have several complications. In particular, it is not certain that only one shell is ejected. There are several planetary nebulae with double shells that cannot be explained otherwise. Perhaps in some systems the phenomenon of shell ejection occurs several times prior to entering the collapse sequence.

3. Theoretical Evolution

There are two families of approaches to the theoretical explanation of the central stars of the planetary nebulae. The first is that the stars are primarily remnant stellar cores, without nuclear fuel burning, going through the gravitational and thermal adjustment necessary for reaching the white dwarf state (Salpeter, 1971; Savedoff *et al.*, 1969; Deinzer, 1967). The second approach is that nuclear burning processes are still important and that helium and hydrogen burning in outer shells occurs (Rose and Smith, 1970; Faulkner, 1968; Paczyński, 1971). Both of these approaches agree in arguing that the stars must be of sufficiently low mass to avoid carbon burning, although not all authors agree on the critical mass for this burning to occur (1.04–1.3 $M_\odot$).

Although arguments of the rate of field stars leaving the main sequence imply that the most common original mass for the system is about 1.3 $M_\odot$, it is unlikely that all of this original mass is still in the star after passing through the horizontal branch stage, since lower masses are required to reconcile the helium burning models with observations. Therefore, a number of original masses can produce the required low mass stars that avoid carbon burning.

Low mass CO stars have been calculated (Beaudet and Salpeter 1969) and are shown in Figure 2 along with the observations. Basically, these are non-burning stars in adjustment. Generally the correct path is followed, but the temperatures are rather high for the required luminosity and the timescales are too long. The real stars must have some light element atmosphere and the theoretical calculations are very sensitive to only a few percent He atmosphere, although it seems unlikely that these models can be brought up to sufficient luminosity and short timescale.

Double shell burning stars have been calculated by Paczyński (1971) with greater success. In this case, he treats in detail the presence of the light element envelope as it is the potential source of most of the energy. The results of his calculations are shown in Figure 3. The timescales are indicated by marks at 10^4 and 10^5 years. The presence of the loops caused by thermal relaxations may be particularly relevant in producing scatter about the average path and to the double shell sources.

In detail, none of the theoretical calculations match the observations; but, the double shell-burning models can probably be matched to them when the problem of correctly handling the atmosphere is resolved. The set of calculations of Paczyński

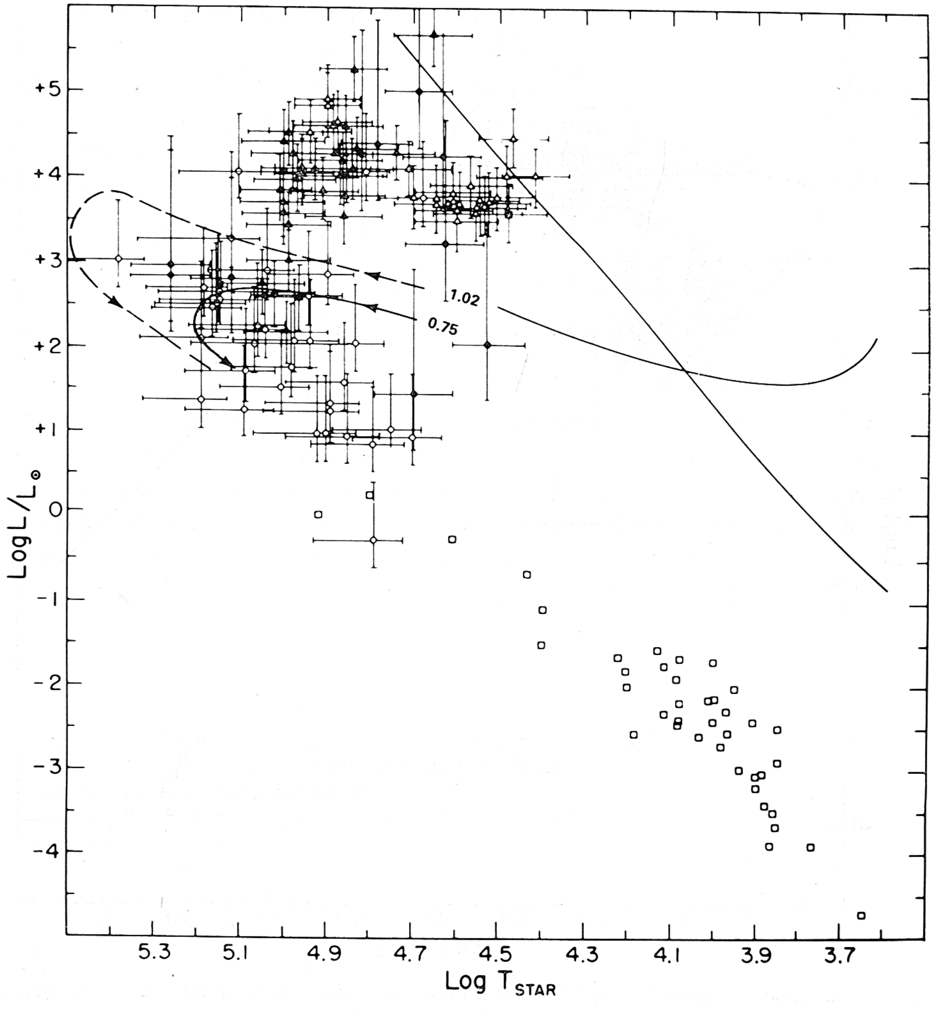

Fig. 2. The same as Figure 1 (without the average evolutionary path) but with the track of 1.02 and 0.75 $M_{\odot}$ carbon-oxygen stars superimposed. The calculated paths shown do not have light element atmospheres, which can alter the path very significantly.

(1971, Figure 2) of nearly exhausted stars with various fractional envelopes dramatically shows the sensitivity to the amount of atmosphere.

The nature of the star immediately prior and during shell ejection is even more uncertain. There are only a few general considerations that one can use for guidelines.

(1) The original star was probably quite large, approximately 200 $R_{\odot}$, since ejection from smaller stars would produce a much wider range of kinetic energies than is observed (Abell and Goldreich, 1966).

(2) The ejected shell has not been mixed with the inner star, since the ejected shells have helium abundances comparable to their initial values and the metal poor

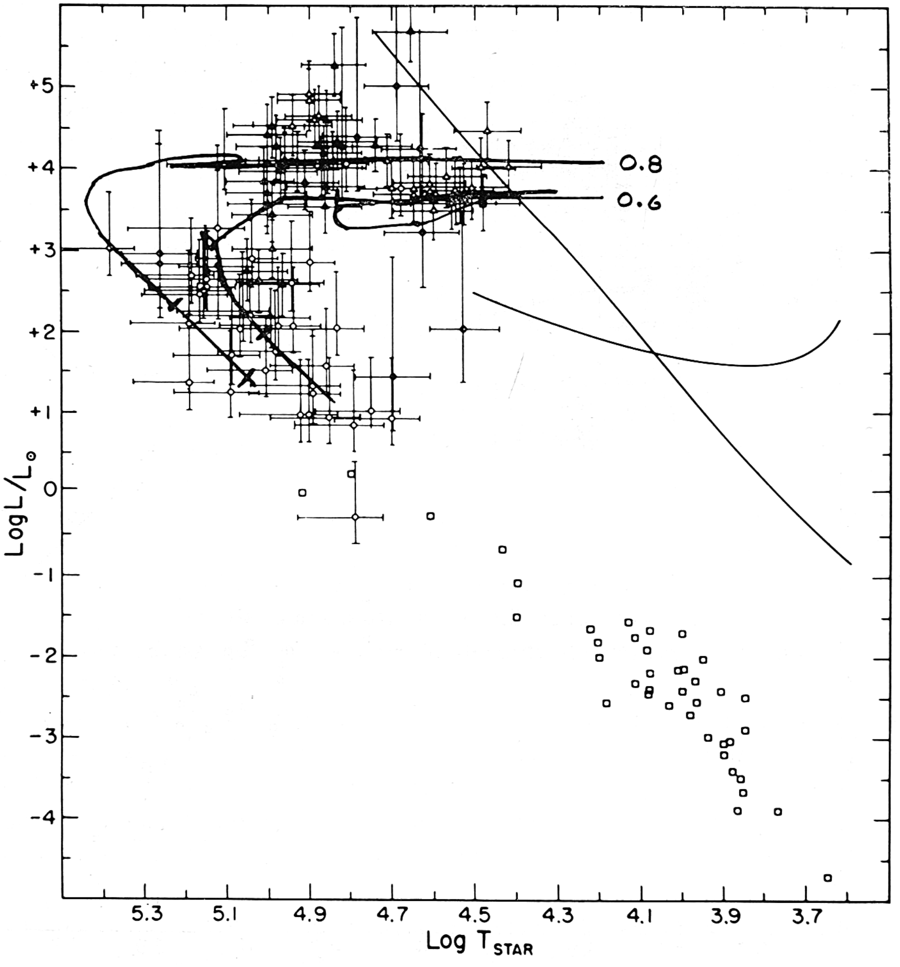

Fig. 3. The same as Figure 2 except that the evolutionary tracks of 0.6 and 0.8 $M_\odot$ shell burning stars as computed by Paczyński (1971) are shown.

globular cluster (M15) planetary has a low metal abundance (O'Dell *et al.*, 1964).

There are currently three approaches to obtaining the ejection: Radiation pressure acting on a star of extended radius (Faulkner, 1970); ionization-recombination equilibrium leading to instabilities; violent thermal relaxations accompanying helium-shell burning flashes (Rose and Smith, 1970). Combinations of these mechanisms may operate together to produce the effect.

In any event, it seems necessary to explain the presence of particulate matter in the ejected shell, which leads to strong thermal infrared emission (Neugebauer *et al.*, 1971). Most likely this is an indication of evolution from a cool-luminous star and requires pushing out the shell prior to the heating up of the star, which would destroy the particles. In addition, there is a growing body of evidence that some of the peculiar late-type stars are precursor planetary nebula systems. Of particular interest along these lines is V1016 Cygni, which has been studied in detail by Baratta *et al.* (1974). They have shown that this star is surrounded by a shell of material ejected earlier and that the central star has only recently ruptured its optically thick atmosphere (producing the late type stellar spectrum) to allow extensive photoionization to occur. We seem to have a similar situation in FG Sge which shows a fossil remnant planetary nebula surrounding a star with an expanding atmosphere possibly representing another shell ejection; but, at a greater time interval than V1016 Cyg. The existence of such a fossil remnant requires that the star did move beyond $T = 30000$ K following the first ejection. Such features together with the observed, resolved double nebulae agree quite well with the loops described by the Paczyński tracks and generally with the multiple thermal relaxations calculated by Rose.

Certainly, more needs to be done both observationally and theoretically. In particular, the burden now seems to be on the observer to study those systems that may be the immediate precursors. In addition, there is the very real possibility of determining the M/R ratio by means of the gravitational redshifts to the central stars by measuring their apparent radial velocities with respect to the nebula. One should not underestimate either the difficulties or advantages of such measurements.

References

Abell, G. O. and Goldreich, P.: 1966, *Publ. Astron. Soc. Pacific* **78**, 232.
Baratta, G. B., Cassatella, A., and Viotti, R.: 1974, *Astrophys. J.* **187**, 651.
Beaudet, G. and Salpeter, E. E.: 1969, *Astrophys. J.* **155**, 203.
Deinzer, W.: 1967, *Z. Astrophys.* **67**, 342.
Faulkner, D. J.: 1968, *Monthly Notices Roy. Astron. Soc.* **140**, 223.
Faulkner, D. J.: 1970, *Astrophys. J.* **162**, 513.
Harman, R. J. and Seaton, M. J.: 1966, *Monthly Notices Roy. Astron. Soc.* **132**, 15.
Liller, M. H. and Liller, W.: 1968, in D. E. Osterbrock and C. R. O'Dell (eds)., 'Planetary Nebulae' *IAU Symp.* **34**, 38.
Neugebauer, G., Becklin, E., and Hyland, A. R.: 1971, *Ann. Rev. Astron. Astrophys.* **9**, 67.
O'Dell, C. R.: 1962, *Astrophys. J.* **135**, 371.
O'Dell, C. R.: 1963, *Astrophys. J.* **138**, 67.
O'Dell, C. R., Peimbert, M., and Kinman, T. D.: 1964, *Astrophys. J.* **140**, 119.
O'Dell, C. R.: 1968, in D. E. Osterbrock and C. R. O'Dell (eds.), 'Planetary Nebulae', *IAU Symp.* **34**, 361.
Paczyński, B.: 1971, *Acta Astron.* **21**, 417.
Perek, L. and Kohoutek, L.: 1967, *Catalogue of Galactic Planetary Nebulae, Academia*, Praha.
Rose, W. K. and Smith, R. L.: 1970, *Astrophys. J.* **159**, 903.
Salpeter, E. E.: 1971, *Ann. Rev. Astron. Astrophys.* **9**, 127.
Savedoff, M. P., Van Horn, H. M., and Vila, S. C.: 1969, *Astrophys. J.* **155**, 221.
Seaton, M. J.: 1966, *Monthly Notices Roy. Astron. Soc.* **132**, 113.
Shklovsky, I. S.: 1956, *Astron. J. Soviet Union* **33**, 315.
Webster, B. L.: 1969, *Monthly Notices Roy. Astron. Soc.* **143**, 113.
Wilson, O. C.: 1950, *Astrophys. J.* **111**, 279.
Zanstra, H.: 1926, *Phys. Rev.* **27**, 644.