Ejection of planetary nebulae by helium shell flashes and the planetary distance scale

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Summary. We investigate a consequence of the hypothesis that planetary nebulae are ejected in the nuclear runaway shell flashes that take place in intermediate mass stars when both hydrogen and helium are burning in thin shells. During this evolutionary phase, a star's luminosity and the time between shell flashes are both (almost) uniquely determined by the star's core mass. Thus, if planetary nebulae with two or more shells are the products of ejection at the same velocity by two or more successive flashes, it should be possible to correlate the separations of the shells with the brightnesses of the central stars. Because linear separation and absolute luminosity are related to angular separation and apparent luminosity by distance and distance squared respectively, this correlation provides a constraint on distances to the objects.

Using data from the literature, we find that the hypothesis is tenable only if the larger of the two distance scales which have been suggested is correct. In this case, the carbon-oxygen cores of the stars apparently have masses of $0.8 \pm 0.15 M_\odot$, which is interesting in connection with measured white dwarf masses. It should be possible in principle to calibrate a new, independent distance scale for the planetary nebulae based upon this hypothesis.

1 Introduction

Shklovskii (1956) first suggested that planetary nebulae are ejected from red giants toward the ends of their lives. Almost everyone now believes this, but there is much less agreement on the mechanism by which the ejection occurs. Defensible scenarios include (a) the development of large-amplitude thermal instabilities in the envelopes (Rose 1967; Smith & Rose 1972), (b) excessive radiation pressure (Bisnovatny-Kogan & Zeldovich 1968), (c) a dynamical instability resulting from positive total envelope energy (Paczyński and Ziołkowski 1968), (d) transfer of angular momentum from the orbit of a close binary central
star to a common envelope (Ostriker & Paczyński 1975; and a prescient remark by Boyarchuk 1968), and (e) ejection during the thermonuclear runaways (shell flashes) which occur in intermediate mass stars when hydrogen and helium are both burning in thin shells. Sackmann, Smith & Despain (1974) suggested this mechanism for eruptive variable carbon stars, and Christy-Sackmann and Despain (1974) and Paczyński (1975) applied it to the curious recent behaviour of FG Sge (the central star of the planetary nebula H_p 1 – 5). We investigate here a test of this last scenario as applied to planetary systems which show more than one gaseous shell.

2 Double-shelled planetary systems

Curtis (1918) recognized that some planetary systems appear to have two concentric shells. The obvious interpretation of such structure — given that the velocity of the outer shell is not larger than that of the inner one; (Weedman 1968) — is that the central star has ejected material on more than one occasion. Gurzadian (1962) has branded this idea as unacceptably naive, citing the absence of triple shells and the physical difficulty of keeping two shells shining. Kaler (1974) and Feibelman (1974) have since found three triple-shelled nebulae, and Wentzel (1976) has apparently solved the physical difficulty with a scheme in which the outer shell is neutral for a time and ionized (or re-ionized) after the inner one has been ejected and become optically thin to ionizing radiation. We therefore adopt the obvious interpretation.

Kaler (1974) gives the most extensive published list of multiply-shelled planetary systems,

Table 1. Properties of planetary nebulae with more than one shell. Separations, $\Delta r$, from Kaler (1974) except for A46 and NGC 7293. Distance scales and stellar luminosities from O'Dell (1962, 1963) and Seaton (1966).

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including 19 objects (17 doubles, two triples), mostly fairly bright (NGC) ones. We looked through the Catalogue of Perek & Kohoutek (1967) and found seven additional apparent doubles (A45, A46, A62, M1 – 67, K1 – 14, NGC 6164 – 5, and NGC 7293) only two of which have sufficient data published for them to appear in the analysis which follows.

Table 1 lists 20 multiply-shelled objects (Kaler’s He 1 – 5 is also inadequately studied for our purposes), and the distances, in arcsec, between inner and outer shells. The table includes the luminosities of the central stars and their distances as given by Seaton (1966) and O’Dell (1962, 1963). These are far from being the most recent distances calculated for the nebulae, but they are the only ones accompanied by sets of consistent central star luminosities, which we shall require shortly. The table gives, finally, the separations in parsecs between inner and outer shells as implied by the two distance scales.

3 Shell flashes and the ejection hypothesis

Schwarzschild & Härm (1967) discovered the existence of nuclear runways in helium-burning shells, now universally called shell flashes. They arise when a nuclear burning shell is so thin that even a rather large expansion of it does not decrease the pressure (by lifting up outer layers) enough to restore a small temperature increase caused by a slight increase in nuclear reaction rate. The behaviour of the energy generation rate, luminosity, convective mixing, and everything else during these flashes is exceedingly complex (Sackmann 1977).

A couple of simple relationships can, however, be extracted. In particular, for a given chemical composition and set of input physics (treatment of opacities, convection, degeneracy, etc.), the core mass interior to the helium-burning shell uniquely determines both the average stellar luminosity and the time between shell flashes, once they are well established (Paczyński 1975). The core mass can be eliminated between the two relationships to give

\[ \log \Delta t_{\text{yr}} = 5.20 - (L/L_\odot)/(1.32 \times 10^6), \]  

where \( \Delta t_{\text{yr}} \) is the time between shell flashes (in years), over the range \( M_{\text{core}} \approx 0.58-0.95 M_\odot \). The relationship has not been calculated for smaller core masses, while for \( M_{\text{core}} > 0.95 M_\odot \), the convective envelope of the star apparently eats into the core during the shell flashes, and soon brings the core mass down again.

Now, if multiply-shelled planetaries are ejected by successive shell flashes, and the ejection velocity does not differ too much among the objects, equation (1) implies that the linear separation between multiple shells should be correlated with the absolute luminosities of the central stars. Observations give (if we are lucky) angular shell separation and apparent luminosity of the central stars. The luck comes in in getting (a) apparent magnitudes for the central stars which are free of nebular contamination, (b) bolometric corrections from some variation of the Zanstra method, and (c) distance-independent reddening corrections from a comparison of optical with radio or infrared data.

But linear separation is related to angular separation and absolute luminosity to apparent luminosity by distance and distance squared respectively. Thus, for a given double-shelled planetary, our hypothesis is consistent with only one distance to the object, which may or may not be the same as that found from other methods. There are two ways of using this fact. One is to assume the hypothesis is correct and make it the basis of a new scale of distances to the planetary nebulae. The other is to consider previous determinations of the distance scale and test the consistency of the hypothesis with them. We adopt the second approach here.
4 Planetary distance scales

Minkowski (1965) and Seaton (1966) have reviewed the history of planetary nebula distance determinations. All recent work makes use of theoretical developments by Menzel (1931), first applied to NGC 3687 by Minkowski & Aller (1954), which show that the total emitted Balmer line flux must be proportional to the ionized hydrogen mass of the nebula. Shklovskii (1956) adapted this by assuming that the ionized mass was the same for each object. If so, then it is only necessary to calibrate a scale on a few planetary of known distance to get distances for all of them. The calibration can be done with nebulae in the Magellanic Clouds and clusters, by spectroscopic parallax of wide companions to central stars, by dynamical methods for nebulae with expansion velocities measured in both km/s and arcsec/yr, or by statistical parallax. All of these have been tried. Over the years, the measured line fluxes, reddening, and absorption values which enter into distance determinations by Shklovskii's method have gradually improved.

Most of the published scales can be divided into two groups, a relatively smaller scale, corresponding to a mean ionized hydrogen mass \( \leq 0.2 M_\odot \) (e.g. O'Dell 1962; Seaton 1968; Webster 1969; Cahn & Kaler 1971) and a relatively larger (by about 50 per cent) scale, corresponding to a mean ionized hydrogen mass \( \sim 0.3-0.4 M_\odot \) (e.g. Seaton 1966; Minkowski 1965; Cudworth 1974).

Any distance scale implies absolute luminosities for the central stars. These do not just scale as \( d^2 \) (even after correction for absorption) because the Balmer line fluxes and reddening corrections (for which different authors have used quite different values) enter into determining the bolometric corrections (by some version of the Zanstra method, using either blackbody or model atmosphere fluxes for the stars) as well as the distances. We have, therefore, chosen the work of O'Dell (1962, 1963) and Seaton (1966) as representative of the small and large scales because only they also derived consistent sets of central star luminosities from the same data that went into their distance determinations.

5 The hypothesis versus the data

Fig. 1 is a plot of time between shell flashes versus central star luminosity. We have assumed an ejection speed of 30 km/s for all objects. The circles are the values using distances and luminosities from Seaton (1966) and the crosses data from O'Dell (1962, 1963). Not all the objects in Table 1 have distances on both scales. The upward and downward pointing vertical arrows represent the amount by which a data point would be moved by decreasing or increasing the expansion speed by a factor of two. The upward and downward pointing diagonal arrows show the amount by which a datapoint would be moved by increasing or decreasing the distance by a factor of two, neglecting all effects of changed absorption and reddening. The solid line is the theoretical relationship of equation (1) for time between shell flashes versus stellar brightness.

Clearly, some of the points are very far away from the curve for either distance scale! Better treatments of bolometric corrections and interstellar absorption could make this situation either better or worse. In the case of the larger scale, however, the curve does at least go roughly through the middle of the points, so that they might be brought onto it by allowing for some scatter in nebular masses, BC's and so forth. This seems much less plausible for the smaller distance scale, for which all points fall below the curve. A hypothesis in which ejection occurred in every n'th flash would correspond to lowering the data points (or raising the theoretical curve) by an amount \( \Delta \log \Delta t_{yr} = \log n \). Any \( n \) greater than 2-3 is evidently excluded for both distance scales. The triple-shelled objects both show smaller separations (smaller \( \Delta t \)'s) for the later pair of ejections. The theory requires this to
Ejection of planetary nebulae by helium shell flashes

Figure 1. Comparison of the helium shell flash ejection hypothesis with observations of multiply-shelled planetary nebulae. The solid line is the relationship, equation (1), expected theoretically (Paczyński 1975) for the time between successive shell flashes versus central star luminosity. Representative points on the curve are marked with the core mass of the corresponding star. The data points are the times between the ejections of the shells of the planeraries listed in Table 1, assuming a constant ejection speed of 30 km/s, versus the luminosities of their central stars. Crosses are for distances and luminosities from O'Dell (1962, 1963; two of these are off scale) and circles for data from Seaton (1966). The upward and downward pointing vertical arrows show the displacement of a datapoint if the correct expansion velocity is a factor of two smaller or larger than the one assumed. The upward and downward pointing diagonal arrows show the displacement of a datapoint caused by increasing or decreasing the distance to an object by a factor of two, neglecting all effects of changing absorption and reddening. The ‘Seaton’ points look as if allowing for scatter in nebular masses, BC’s etc. might move them onto the solid curve at positions corresponding to core masses of $0.8 \pm 0.15 M_\odot$.

happen, because a star's core mass must increase with time, increasing $L$ and decreasing $\Delta t$, but the observed effect is bigger than expected. Perhaps the earliest ejections normally have the largest energies and expansion velocities.

If we suppose for a moment that the hypothesis is correct and force the ‘Seaton’ points onto the theoretical curve by arbitrary variations in the nebular expansion velocities and distances, then the displaced points seem to cluster around core masses of $\sim 0.8 M_\odot$, with a range of at least $0.65 - 0.9 M_\odot$. The central stars should, therefore, give rise to white dwarfs of about $0.8 M_\odot$, at the high end of the probable range of typical white dwarf masses, $0.60 - 0.87 M_\odot$ (Trimble & Greenstein 1972; Wegner 1974). This is reasonable, since by focusing on nebulae which are bright enough to be well-studied and central stars which are luminous enough to keep two shells ionized, we have systematically picked out objects more massive than the average.

6 Conclusions

(1) The hypothesis that multiply-shelled planetary nebulae result from ejection of matter during successive helium shell flashes is viable provided that the correct planetary distance scale is one of the larger ones presently in the literature.

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(2) The data (Fig. 1) then look as if the points could most comfortably be moved onto the theoretical curve for core masses of $0.8 \pm 0.15 M_\odot$. This is in good accord with the range of measured white dwarf masses.

(3) The authors contemplate with some trepidation a recalibration of the planetary distance scale based on the present hypothesis. Contributions from readers in the form of unpublished data on fluxes from the relevant nebulae or their central stars at any wavelength, reddening corrections, suitable model atmospheres, or general advice and encouragement would be very welcome.

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References