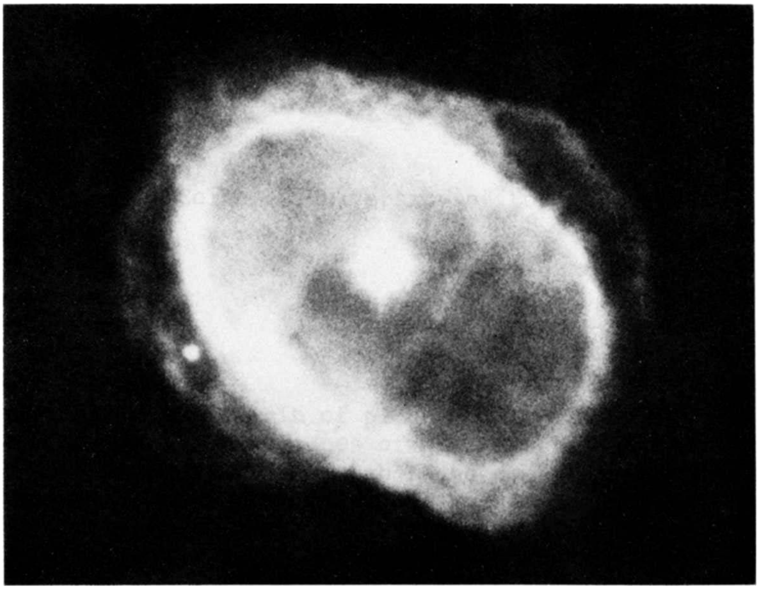

NGC 3132

SESSION VII

THE ORIGIN OF PLANETARY NEBULAE

https://doi.org/10.1017/S0074180900143219 Published online by Cambridge University Press

ORIGIN OF PLANETARY NEBULAE

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1. INTRODUCTION

My interest in the origin of planetary nebulae goes back to 1967 when I proposed that the envelopes of giants with degenerate carbon-helium cores were dynamically unstable and would be completely ejected to form a planetary nebula. Essentially the same proposal was made almost simultaneously by Lucy (1967) and Paczyński (1967). For some years after that I worked on the dynamical ejection with W. van der Reijden, but for the last few years my interests have been in other areas, principally solar physics and gravitation theory. What then can I contribute to a discussion on Planetary Nebulae? Not a detailed review of work in this area; for that, the reader is referred to review articles by Salpeter (1971), Osterbrock (1973) and Miller (1974).

The theoretician working in solar physics faces different problems from his colleagues in stellar physics, particularly from his colleagues working on stellar evolution and the ejection of planetary nebula shells. The solar physicist has an abundance of observational data and he cannot easily get away with highly idealised theories. He has not been notably successful in explaining the embarassingly detailed observations; he cannot explain the heating of the corona, the supergranulation, the electron proton and helium temperatures in the solar wind, the solar Lithium Beryllium and Boron abundances, the solar oscillations and those under-abundant neutrinos. This has made me somewhat more reluctant to accept that the theoretical models we use in stellar physics are quite as valid as is usually believed and it is this (healthy) scepticism that I wish to contribute to a discussion on the origin of planetary nebulae. I cannot do better than to remind you of the words of John Locke (1689), the "founding father" of British empiricist philosophy:

> "it is therefore worthwhile to search out bounds between opinion and knowledge, and examine by what measures in things whereof we have no certain knowledge we ought to regulate our assent and moderate our persuasions"

With these words ringing in our ears, what can be said about the origin

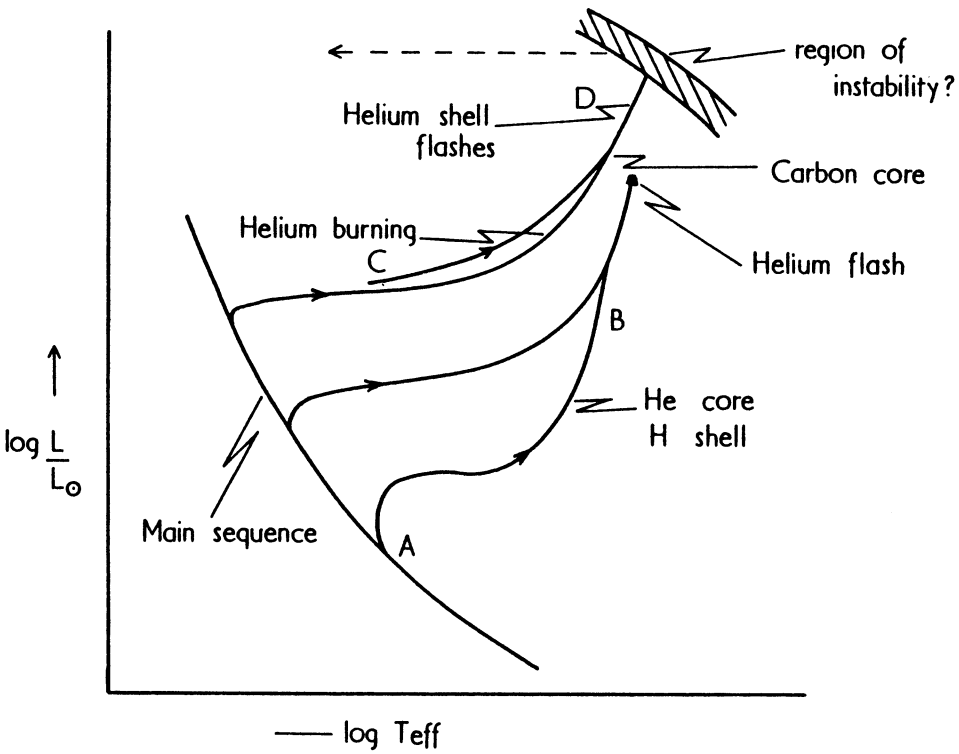
Yervant Terzian (ed.),Planetary Nebulae, Observations and Theory, 295-303.

of planetary nebulae? From the observational side there is sufficient evidence to advance the hypothesis that the progenitors of planetary nebulae are luminous red giants (c.f. Osterbrock 1973); we shall take this as a working hypothesis. Our first task is to see what the theory of stellar evolution has to say about the internal structure and evolution of stars from the main sequence to the giant phase. Our second task is to highlight the uncertainties in these calculations. Next, we consider various proposed theories and comment on them. Finally, we consider the problem of binary stars.

2. THE THEORY OF STELLAR EVOLUTION

The results of calculations on the evolution of stars are sketched in Figures 1 and 2. On the main sequence, stars convert hydrogen into helium in their central regions; stars like the sun have no central convective zone, but more massive stars do. After the exhaustion of hydrogen, the star's helium core contracts, for stars $M \lesssim 2.5M_{\odot}$ degeneracy pressure halts the contraction, and they take up a giant structure with a hydrogen burning shell. When the core mass grows to about

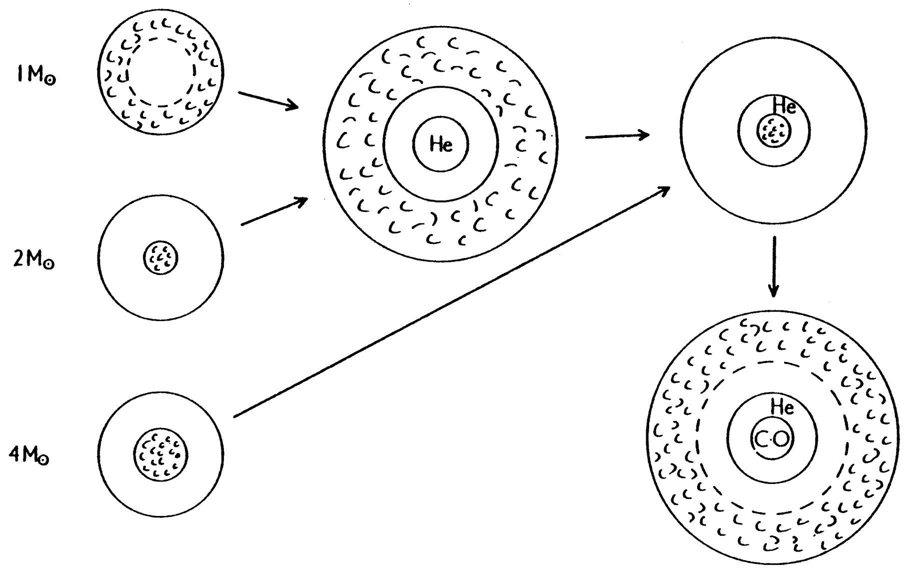
FIGURE 1



Evolution of Stars

FIGURE 2

Internal Structure of Stars



$0.5M_{\odot}$, helium ignites in the degenerate core giving rise to the helium flash leading to a non-degenerate helium burning core, and the star now resembles its more massive counterpart that went straight to helium burning after main sequence hydrogen exhaustion.

After helium exhaustion in the core, stars with $M \lesssim 7M_{\odot}$ develop a degenerate carbon-oxygen core, a helium burning shell, a helium intermediate region, a hydrogen burning shell and a hydrogen envelope. During this next phase of evolution, the helium shell burning goes through thermal pulses in which the luminosity of the shell rises to very large values $\sim 10^6\ L_{\odot}$, although for very short times. At this stage the total luminosity of the star is large, 10^3-$10^4\ L_{\odot}$ and the radius is very large $\sim 200\ R_{\odot}$, so the model stars have the properties of red giants. At this stage of evolution we believe that stars $\lesssim 4M_{\odot}$ eject their hydrogen envelopes to form planetary nebulae, the remnant core evolving to become a white dwarf. Qualitatively the scheme fits the observed data.

3. PROBLEMS IN STELLAR EVOLUTION THEORY

Detailed quantitative models of stellar evolution, of which there are very many in the literature, can, however, only be developed under certain simplifying assumptions - and it is here that we have to "search out the bounds between opinion and knowledge". Let me examine a few problem areas.

3.1 Convection

The "theory" of turbulent convective energy transport used in astrophysics is wrong: the only question is how wrong is it? The problem is to determine the average value of fluctuating variables in the energy equation of a fluid. In the astrophysical model, several assumptions are made - first, that the layer is thin compared to a scale height, secondly, that viscous dissipation is negligible and finally, that the remaining energy transport term can be estimated by assuming "blobs" of fluid travel a mixing length conserving entropy and in pressure equilibrium with the surrounding medium. All these assumptions are of dubious validity and the thin layer approximation is not valid. The errors in the theory are likely to be significant in estimating the extent of convective overshooting at the boundary of convective zones, the structure of low temperature convective envelopes and the magnitude of convective velocities (c.f. Roxburgh 1976). The problem is even more severe when considering time dependent convection. Unfortunately, we are still a very long way from developing a correct theory, but results that are dependent on the "theory" of convection should be considered with caution.

3.2 Coronal Driven Mass Loss

The sun has a corona and resulting mass loss in the solar wind. However, the theory of these phenomena is poorly understood and extrapolation to other stars, though necessary, should be treated with caution. It is generally believed, though not proven, that the corona is heated by the dissipation of acoustic or magneto-acoustic waves that are generated by the turbulence in the convective zone. The rate of conversion of turbulent convective kinetic energy into acoustic wave energy in subsonic turbulence is generally taken to be proportional to the Mach number to the eighth power. If the turbulence becomes sonic, a very large fraction of the energy flux could end up as waves and ultimately as mass loss. The rate of this mass loss and hence its terminal speed will need a theory analogous to that of the solar wind, and this theory is not well understood, particularly the plasma turbulence and energy transport (c.f. Singer and Roxburgh 1977).

3.3 Rotation and Magnetic Fields

Attempts to include rotation and magnetic fields in stellar evolution are still in their infancy. However, the simple observation that in non-rotating models of stellar evolution the central density increases by factors of the order of 10^6 should make us cautious since a contraction of the central regions would increase the ratio of magnetic and/or rotational energy to gravitational energy, producing substantial departures from spherical symmetry and possibly dynamical instability. If a turbulent dynamo operates in the surface convective zones of giants, it could play a major role in controlling or at least influencing the geometry of mass loss.

3.4 Physical Processes

There still remain uncertainties over the opacity of stellar material and neutrino energy losses.

3.5 Dynamical Phases

At certain stages of stellar evolution, the helium flash, shell flashes, mass ejection, oscillations, etc., it is necessary to follow the dynamical evolution on a very short time scale. Substantial progress has been made on one-dimensional models, but very much less on two or three-dimensional hydrodynamics, and anyway, these problems often require a model of time dependent convection.

4. THEORIES OF NEBULA EJECTION

While we must regard any models with caution, this is no excuse for inaction; can we give at least qualitative reasons for a star to eject its envelope to form a planetary nebula? Several suggestions have been proposed drawing on some of the expected properties of evolved giants. These properties are:

(a) A degenerate carbon-oxygen core, helium and/or hydrogen burning shells, probably significantly distorted by rotation and magnetic fields

(b) Thermal flashes given very dramatic increases in the helium shell source luminosity $L_{He} \sim 10^6\ L_{\odot}$

(c) The total luminosity is very large and radiation pressure becomes comparable to gravity $L \sim 4\pi cGM/\kappa$

(d) The star has a very large radius and therefore a very small escape speed $\sim$30 km/sec

(e) The surface layers are very cool and have significantly deep ionization zones, the total energy in the envelope, gravitational kinetic and ionization energy becomes positive

(f) The stars have very vigorous sonic convection and therefore probably coronae and coronally driven mass loss.

Giant stars have another property that is probably significant; the central and surface regions do not react back on each other. For instance, the luminosity of the star is determined by the core mass and not by the envelope mass. The radius on the other hand is determined by the luminosity and not by the envelope mass. Thus, if the star is unstable, losing mass does not stabilize the star, so that complete ejection of the envelope is probable.

The helium shell flashes led Rose (1966) to propose that these grew in amplitude until they led to mass ejection, perhaps in bursts rather than continuously. Faulkner (1970) and Finzi and Woolf (1971) proposed that as the luminosity approaches the Eddington limit, the envelope is forced out by radiation pressure. In the Rose model the energy for ejection comes from the helium shell flash; in the Finzi, Finzi and Shaviv (1974) model the energy comes from a hydrogen burning shell.

The dynamical instability model proposed by Lucy (1967), Roxburgh (1967) and Paczyński and Zilkowski (1968) is driven by the low value of γ in the deep ionization zones and by the fact that the total energy of the envelope is positive (gravitational, thermal and ionization); the energy of recombination can, in principle, lead to envelope ejection. Early studies by Paczyński, Zilkowski and myself found such instabilities from an adiabatic analysis, but since the thermal and dynamical times are comparable a more sophisticated analysis was needed. This was undertaken by Keely (1970) who undertook a detailed non-linear, non-adiabatic analysis, and found finite amplitude oscillations with periods comparable to those of the Myra variables, but no ejection. Subsequent calculations by Smith and Rose (1972) found a small amount of ejection leading them to suggest that the star ejected many small mass shells. Kutter and Sparks (1974) and Spry (1975) repeated these calculations for higher luminosities and found oscillations of Myra type giving way to total envelope ejection for large luminosities. Table 1 gives some of these results.

TABLE 1

$M = 1{\cdot}1M_\odot$, $M_c = 1{\cdot}0M_\odot$

$L/L_\odot$	Log R	Log T_{eff}	Period (yrs)
3100	13.04	3.55	0.5
6500	13.25	3.54	1.1
9200	13.31	3.53	1.4
12,000	13.36	3.53	1.7
19,000		EJECTION	

However, the details of these models depend on the assumptions that went into their calculations, and in particular the question of whether the star loses its envelope by multiple ejection or one single ejection remains unanswered.

The whole problem is complicated by the neglect of acoustic or magnetic acoustic wave generation in the convective zone and the probability of chromosphere/corona production and an associated wind. The oscillations in the Myra phase would also produce acoustic waves and a corona so we should expect mass loss by a wind during the Myra phase. If we attempt to estimate the production of noise and extrapolate from the solar case we find very large mass loss rates, increasing with increasing stellar luminosity. By the time the luminosity has risen to $10^4L_\odot$, the whole envelope could just evaporate in a time of 10^4 years.

At the present time, we should not 'believe' any of the theories, but quite probably many of the effects are important. For example, as the star increases in luminosity we might expect (a) increasing wind loss, (b) Myra-like dynamical oscillations, (c) decreasing envelope mass from the wind, (d) occasional small shell ejections caused by He shell flashes, (e) dynamical ejection of the remnant envelope, (f) acceleration of the ejected envelope by radiation pressure. However, all the 'models' suffer from the difficulties in modelling the structure and dynamics of stars, and without a dramatic advance in turbulence theory the answers are more likely to come from observation than theory.

5. BINARY STARS

One possible test on theories is if the remnant star is a binary. Recently, Mendez and Niemela (1977) have reported that the central star in NGC 1360 is a spectroscopic binary with a period of 8 days and a total mass of the order of a solar mass. This is difficult to reconcile with most theories, but particularly with the dynamical instability model since the maximum dimension of the system is only of the order of 20 $R_{\odot}$, not 200 $R_{\odot}$. If more binary systems are found, this will be of considerable value.

Finally, one may conjecture that Sirius B is the remnant of a planetary nebula. Here the stars are well-separated and should have evolved without interaction; if the orbit was originally circular, then for the present eccentricity to be 0.6, Sirius B must have had a mass of 3 $M_{\odot}$ before envelope ejection. This is in reasonable agreement with models which predict a remnant core of order 1 $M_{\odot}$ from a star of mass 3 $M_{\odot}$.

6. CONCLUSION

In the introduction, I quoted the advice of John Locke; if we heed that advice it is clear that while there are several plausible schemes for the origin of planetary nebulae, we should "regulate our assent and moderate our persuasions". There is much to be done before we can, or at least before I can, "believe" any one theory. If I am to single out the major problem, it is turbulent convection. While convection is important at all stages of stellar evolution, it is particularly in the late giants that are thought to be the precursors of planetary nebulae that the theory is needed in detail, and that theory is lacking. Instead, the astronomer falls back on the mixing length theory because he has to use something; unfortunately, it looks as though he will have to do so for many years to come. I also feel that asymmetric effects will be important, particularly if the driving mechanism is sited deep down inside the star - this could possibly give rise to the asymmetries in the ejected nebula. Perhaps we are right to think that planetaries come from double shell source stars, but I think it will need a great deal of work before we can be sure how the shell is ejected.

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DISCUSSION

Kaler: Would you comment on the possibility that it is not just one process, but perhaps many of them which act to produce different kinds of shells at different points in a star's lifetime?

Roxburgh: I don't think on theoretical grounds we are able to say which of these processes is the one that happens or is the one that happens first. There are just too many uncertainties in evolving stars to that stage.

Terzian: Could the observed evidence of 'multiple envelopes' put restrictions on some of the models of ejection which you described?

Roxburgh: The earlier suggestion by Rose was that if you got at least a thin shell and helium shell flashes then maybe you got a set of nebular ejections. The only way in which ejection has been numerically demonstrated has been for complete ejection. I certainly think it is possible that you could get small ejections triggered by shell flashes.

Field: We observe steady-state winds from red giants, but the planetary phenomenon seems to be much more impulsive. In your discussion, the two phenomena seem to be interrelated. Would you clarify the distinction?

Roxburgh: Yes, you get a large mass loss in a steady wind up until the stage where you have reduced the envelope mass to a relatively small amount and then that is ejected cleanly following the wind that has been ejected before.

Aller: Can one predict the chemical composition of the ejected layers?

Presumably, it will depend on the masses of the precursor star.

Roxburgh: One can make predictions, but they depend on the assumptions you put in, particularly the properties of convection at the bottom of the convective envelope.

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