THEORY OF EVOLUTION OF CENTRAL STARS OF PLANETARY NEBULAE

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ABSTRACT

Young central stars of planetary nebulae burn hydrogen and helium in the shell sources. Within less than 10^4 years nuclear fuel is exhausted and old central stars cool off at almost constant radius to the white dwarf stage.

Young, i.e., luminous central stars should follow complicated loops on the H-R diagram as a result of helium shell flashes. FG Sagittae is the example. This should be a typical behaviour and a systematic search for light variations on a time scale of years or decades among other luminous central stars should be undertaken. Because of rapid evolution of their nuclei many planetary nebulae may be far from the ionization equilibrium. This should be taken into account when the effective temperature and bolometric luminosity of the central stars are estimated.

More than a decade ago O'Dell (1963) and Seaton (1966) discovered that the position of a central star on the H-R diagram is well correlated with a linear size of a planetary nebula. Small nebulae had larger, brighter and cooler central stars. Expansion velocity of a typical planetary nebula is 30 km s^{-1} and the largest observed nebular radius is about 0.6 pc. Therefore, the age of the largest nebulae is about 2×10^4 years. Within this short time the radii of central stars decrease by a factor of one-hundred. The oldest nuclei are as small as degenerate dwarfs (O'Dell 1963, 1968).

Shklovsky (1956) presented the hypothesis that planetary nebulae are formed from expanded envelopes of red giants and supergiants. Abell and Goldreich (1966) presented a lot of arguments supporting this hypothesis. It is commonly assumed that the hypothesis is correct, and I make the same assumption in this presentation. At the same time we have to admit that the mechanism responsible for the expulsion of stellar envelope is not known. Nevertheless the red giants and supergiants are observed to lose mass at a considerable rate, and it is natural to look at them as the ancestors of planetary nebulae.

Distribution of planetary nebulae in the Galaxy indicates that most of them are products of evolution of stars not much more

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massive than 1 $M_\odot$ (Shklovsky 1956; Abell and Goldreich 1966; O'Dell 1963; Seaton 1966). Nevertheless we should keep in mind the possibility that a small fraction of planetary nebulae may be much more massive and their central stars may be massive too. Population I Wolf-Rayet stars with so called ring nebulae around them may be an example (Smith 1968, p. 41; 1973, p. 139). I shall consider here, almost exclusively, the most common solar mass progenitors of planetary nebulae. The early theoretical work on this subject was reviewed by Salpeter (1971).

Theory of evolution of solar mass stars is very well developed (Iben 1974). A star stays on the main sequence while burning hydrogen in the core. After hydrogen is exhausted in the core the star becomes a red subgiant and later a red giant. Now hydrogen burns in a shell. As a result, matter flows from the envelope into the degenerate core. Core mass and stellar luminosity increase with time. By the time the core mass is 0.45 $M_\odot$, and luminosity is 2×10^3 $L_\odot$, the core temperature is high enough for helium ignition. Helium flash and core helium burning follow. Stellar luminosity decreases to 50 $L_\odot$. Population II stars become fairly hot and form a horizontal branch. Population I stars remain cool and form a clump on a giant branch. After some 10^8 years the helium is exhausted in the core and a double shell burning follows. The star goes up the asymptotic branch on the H-R diagram and becomes a red giant, and later a red supergiant. Matter flows from the extended envelope into the degenerate core. Core mass and stellar luminosity increase with time up to 1.4 $M_\odot$ and 5×10^4 $L_\odot$, respectively, provided there is enough matter for such a growth.

Helium shell burning is thermally unstable (Schwarzschild and Härm 1965) and the star evolves through a number of helium shell flashes. During a given flash cycle the surface luminosity oscillates by a factor 2.

Effective temperature changes very little as long as the star has a massive hydrogen envelope. Stellar luminosity depends mainly on the core mass (Paczyński 1970, Uus 1970). The luminosity averaged over the flash cycle satisfies the relation

$$L/L_\odot = 2.8 \times 10^4 + 5.9 \times 10^4 \ (M_{core}/M_\odot - 1.0) \qquad (1)$$

for $0.6 < M_{core}/M_\odot < 1.37$. The time interval between the shell flashes, Δt, depends mainly on the core mass (Christy-Sackmann and Despain 1974; Paczyński 1975), and satisfies the relation

$$\log \Delta t \ (\text{years}) = 3.0 - 4.5 \ (M_{core}/M_\odot - 1.0), \qquad (2)$$

for $0.55 < M_{core}/M_\odot < 1.37$.

Surface luminosity at a red giant or supergiant does not depend on the envelope mass, and, therefore, it is not affected by the mass loss. We may expect that progenitors of planetary nebulae should be as bright as young central stars, i.e., their luminosity should be about 10^4 $L_\odot$. This implies that the relevant red supergiants are in the double shell burning phase of evolution, as this is the only phase during which a solar mass star may achieve the luminosity of 10^4 $L_\odot$.

It is not known how the final phases of mass loss take place and how rapid they are. Observations indicate that young and dense planetary nebulae have central stars with log $T_e = 4.5$ (O'Dell 1968). Given the theoretical core mass-luminosity relation we may ask how much mass should be left in the hydrogen rich envelope for the star to have log $T_e = 4.5$. For the core of 0.6 $M_\odot$ the luminosity is 5×10^3 $L_\odot$ and the envelope mass is 4×10^{-4} $M_\odot$. For a core mass of 1.2 $M_\odot$ the luminosity is 4×10^4 $L_\odot$ and the envelope mass is 10^{-6} (Paczyński 1971). The central star radius is 3 $R_\odot$ and 8 $R_\odot$ for the two cases, respectively. A star burns hydrogen and helium in the shell sources at a rate proportional to the stellar luminosity. All the hydrogen rich envelope present when log $T_e = 4.5$ is burnt out in 10^4 years for the 0.6 $M_\odot$ case and in 2 years (yes, two years) for the 1.2 $M_\odot$ case. Within this time the stellar radius decreases to only 0.02 $R_\odot$ or less, and the star evolves horizontally to the left on the H-R diagram. Subsequently, the star cools off at almost constant radius and after a long time becomes a white dwarf (Rose and Smith 1970; Paczyński 1970). There is no real problem with theoretical explanation of the rate at which the radii of central stars decrease. It is striking how strongly the theoretical rate depends on the stellar mass.

We may expect that evolution of models to the left on the H-R diagram is complicated by helium shell flashes. When envelope mass is small the effective temperature of a star may vary a lot during a flash cycle. As a result a star may make very complicated loops on the H-R diagram. The observed changes of FG Sagittae (Herbig and Boyarchuk 1968) are most likely due to a helium shell flash (Paczyński 1970, 1971). Recently Härm and Schwarzschild (1975) published several detailed evolutionary tracks for flashing central stars which were started with fairly realistic initial conditions. More work of this type is needed to explore the variety of possible evolutionary patterns and evolutionary time scales.

Even with a very limited number of published evolutionary tracks one theoretical conclusion is obvious. All very bright nuclei of planetary nebulae, i.e., those with $L > 2 \times 10^3$ $L_\odot$, should be burning hydrogen and helium in the shell sources. As the observed effective temperatures of central stars are high the masses of their envelopes must be very small. This implies that during the helium shell flash the radius and effective temperature of the central star may change rapidly, very likely on a time scale of years or decades. FG Sge should not be a unique case, but rather a typical luminous central star. Clearly, more accurate photometry is needed to detect the likely light changes of luminous central stars.

So far I have ignored the puzzling early part of the Seaton evolutionary sequence. Seaton (1966) claimed the observations indicated that during the very early stages of nebular expansion the luminosity of central stars increased from 10^2 $L_\odot$ to 10^4 $L_\odot$. This kind of increase cannot be explained theoretically with models originating from solar mass giants or supergiants, with most of their envelopes stripped off. The original Seaton's claim was based on a few uncertain observational points, and it is not clear to me that the initial luminosity rise is indeed present. If confirmed, this rise may be difficult to explain theoretically.

Another obvious problem with the evolutionary scenario presented here is caused by very high effective temperatures, up to 5 x 10^{5}°K, which many theoretical models achieve when their hydrogen and helium shell sources die out. There are no central stars known to be so hot. The discrepancy may be due to some error or over-simplification of the models. The choice of initial conditions and the assumption of no mass loss from the central stars are perhaps the most likely source of uncertainty. However, there may be serious observational uncertainties too. Central stars of some planetary nebulae are too faint to be seen. Perhaps these stars are so faint visually because they are very hot. The effective temperatures and bolometric luminosities are estimated for central stars with Zanstra method under the assumption that nebulae are in ionization equilibrium. This assumption is violated when the central star evolves on a time scale shorter than the ionization and/or recombination time scale. A nebula around FG Sge is a perfect example. There may be many more nebulae which provide us with the information about the far ultraviolet radiation of the central stars as it was 10^{2} or 10^{3} years ago, not as it is now.

It is my impression that there is a basic agreement between the available theoretical models of central stars and their observed properties, and that the evolutionary status of the central stars is correctly presented in this paper. More detailed comparison may be possible provided more detailed and precise observations become available. First, a systematic search for FG Sge-type objects should be made among the luminous central stars. Second, new methods of estimating effective temperatures and bolometric luminosities of central stars have to be developed, with the possible departure from the ionization equilibrium in the nebulae taken into account.

The main difficulty that model evolutionary computations face is the uncertainty of the mass loss rate from red giants and supergiants and luminous nuclei of planetary nebulae. As a result, the details of loops that models are making on the H-R diagram are very uncertain. But it is certain that evolution should be very rapid while the central stars are luminous and while they burn hydrogen and helium in the shell sources. As soon as nuclear fuel is exhausted the models cool to the white dwarf stage at almost constant radius. The rate of cooling may depend on the neutrino emission.

There may be at least two other possible types of central stars. Krzemiński, Priedhorsky and Miller (1976) discovered that UU Sge, a central star of a planetary nebula Abell 63, is a short period eclipsing and spectroscopic binary. Another short period binary central star has been discovered by Mender and Niemela (1977). These may be progenitors of short period binaries like V471 Tauri and/or catalysmic variables (Paczyński 1976). No theoretical models are available for binary central stars, and it is not known how common they are. It is possible that at least some massive Population I red supergiants give rise to massive planetary nebulae. It is possible that ring nebulae seen around some Wolf-Rayert stars belong to this category (Smith 1968, 1973). Central stars of these objects are likely to be massive helium stars. Their lifetime and luminosity may considerably exceed the limits that apply to models with degenerate core and shell sources. In particular, no central star with degenerate core may have a luminosity in excess of 5×10^4 $L_\odot$. If a central star more luminous than this limit is found we may be sure it is a massive star of Population I.

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