ON THE EVOLUTION OF CENTRAL STARS OF
PLANETARY NEBULAE

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Abstract. The evolution of nuclei of planetary nebulae has been calculated from the end of the ejection stage that produces the nebulae to the white dwarf stage. The structure of the central star is in agreement with the general picture of Finzi (1973) about the mass ejection from the progenitors of planetary nebulae. It has been found that in order to obtain evolutionary track consistent with the Harman-Seaton track (O'Dell, 1968) one has to assume that the masses of the nuclei stars are less than \( \sim 0.7 M_\odot \). The calculated evolutionary time scale of the central stars of planetary nebulae is \( \sim 2 \times 10^4 \) yr. This time scale is negatively correlated with the stellar mass: the heavier the stellar mass, the shorter the evolutionary time scale.

1. Introduction

The central stars of planetary nebulae are observed to evolve toward the white dwarf (WD) stage on a relatively fast time scale of the order of \( 10^4 \) yr (Seaton, 1966). The basic observational facts are the following:

(1) The youngest observed planetary nebulae appear to have an age, as judged by their expansion velocities (20 km s\(^{-1}\)) and their present diameters (\( \sim 0.04 \) parsec, depending on the distance scale, Cahn and Kaler, 1972) of only 2000 to 3000 yr (O'Dell, 1963). For the ejected nebulae to be observable as planetary nebulae, the surface temperatures of the central stars must be at least \( T_e \sim 4 \times 10^4 \) K. This implies that the nuclei of a planetary nebulae (NPN) have to evolve from the progenitors configurations at the end of the ejection stage to blue nuclei stage with \( T_e = 4 \times 10^4 \) K in a short time scale of, at most, a few thousand years.

(2) In the initial stages of the nebulae expansion, when \( 0.04 < R_{\text{nebula}} < 0.1 \) parsec, the observed emission power of the central stars has considerable scattering, \( \log (L/L_\odot) = 3 \) to 4, and the effective temperatures are \( T_e = 4 \times 10^4 - 6.5 \times 10^4 \) K. If the interpretation of observations is based on evolutionary track of a nucleus of single mass and composition, then the data imply positive correlation between the star’s temperature and bolometric magnitude (Webster, 1969).

(3) Nebulae with observed radii of \( 0.1 < R_{\text{nebula}} < 0.3 \) parsec, are often optically thin in the Lyman continuum. From the observed nebulae radii and the measured temperatures and luminosities of the central stars it is concluded that in this stage stars evolve through increasing effective temperatures, \( T_e = 6.5 \times 10^4 - 10^5 \) K with approximately constant bolometric luminosity \( \log (L/L_\odot) \sim 4 \). The maximum measured
effective temperatures in this stage depend somewhat on the adopted Zanstra temperature scale – the temperatures may be considerably higher than $T_e \sim 10^5$ K (Harman and Seaton, 1966). The total radiative energy emitted during this stage is of the order of $4 \times 10^{48}$ erg.

(4) Nebulae which have been expanded beyond $R_{\text{nebula}} > 0.3$ parsec, are found to be optically thick in the Lyman continuum. The observed bolometric luminosities of the central stars are comparatively low, $\log (L/L_\odot) \sim 4$ to 1, and the effective temperatures $T_e \sim 10^3 - 5 \times 10^4$ K. The faintest observed central stars are comparable in temperature, luminosity and spectra to some of the hottest known white dwarfs (O'Dell, 1968).

(5) Large fraction of the central stars in young nebulae display Wolf Rayet (WR) type spectra which presumably implies steady mass loss from the stars to the nebulae. Statistical arguments favor the hypothesis that all central stars pass through WR stage after the ejection of the nebulae (O'Dell, 1968).

(6) The surface composition of the central stars may be different from that of the nebulae. Spectra analysis of the atmospheres of these stars suggests that the characteristic WR emission lines are either of the carbon sequence or the nitrogen sequence (Aller, 1968). The nebulae are found to be overabundant in nitrogen: the ratio N/O in planetary nebulae is about 5 times higher than in H II regions (Peimbert and Torres-Peimbert, 1972).

(7) The average mass of planetary nebulae can be derived from the estimated distances and filling factors; according to Seaton (1968) the average mass of the ionized gas in planetary nebulae is $\sim 0.17 M_\odot$. O'Dell (1963) has shown that the mean height of planetaries above the galactic plane is the same as that of the stars of mass of about 1.2 $M_\odot$. Therefore, the average mass of the central stars must be less than one solar mass.

The theoretical work in this field has been concentrated on two important problems:

1. Explanation of the mechanism that drives the ejection of the nebulae, and
2. Prediction of the evolutionary track (Harman-Seaton track) of the central stars of planetary nebulae. Whereas the possibility of mass ejection from stars has been demonstrated in several works (Keeley, 1970; Smith and Rose, 1972; Kutter and Sparks, 1974; Stry, 1975; Barkat and Tuchman, 1977), there is still some controversy on the theoretical explanation of the observed evolution of NPN's. It has commonly been suggested that progenitors of planetary nebulae are red giants (Abell and Goldreich, 1966) with highly evolved cores. The estimated central temperatures and densities of these progenitors are $T_c \sim 100-200 \times 10^6$ K, and $\rho_c \sim 10^5-10^7$ g cm$^{-3}$ depending on the total stellar mass (Salpeter, 1971).

Numerous evolutionary calculations of stellar models composed of heavy elements core ($A \geq 2$) and light, hydrogen-rich envelope ($m_{\text{envelope}} = 0-0.01 M_\odot$) were carried to the stage of white dwarf formation in order to predict the observed evolutionary track of the NPN's. Roughly, these models can be divided into two groups according to the assumed source of the observed radiative flux: (1) Gravitational contraction with core