PLANETARY NEBULAE: THEIR EVOLUTION AND ROLE IN THE UNIVERSE
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Hot Haloes of Planetary Nebulae

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Abstract. We present model results of time-dependent ionization of a nebula with a halo. Fast transition of the ionization front across the halo causses its heating well above the equilibrium temperature. For a long time after this event the halo is observed as hotter than the main inner nebula, in agreement with observations of some planetary nebulae.

Spectroscopic investigations show that outer haloes of some planetary nebulae are hotter than the main nebulae (e.g. Middlemass et al. 1989; Hyung et al. 2001). This cannot be accounted for by steady-state photoionization models. Usually, it is interpreted as a result of shock heating (e.g. Hyung et al. 2001).

We investigate another mechanism which is due to non-steady photoionization and heating of outer thin nebular regions. It results from the evolution of the nebula and the central star. Due to the increase of the effective temperature of the central star and the expansion of the nebula, the ionization front moves further and further in the nebular material. When it breaks through the main dense nebula and enters the thin gas it moves very quickly across the halo and heats it up. Due to the long cooling time the electron temperature in the thin halo can be significantly above the equilibrium value for a long time.

We have carried out time-dependent calculations of a expanding model nebula ionized by the radiation field from an evolving central star. The central star evolved according to the $0.644\,M_\odot$ model of Schönberner (1981). The time-dependent ionization calculations started when the effective temperature of the central star reached $1\,10^4$ K. At this moment the main nebula with a constant (hydrogen) density of $1.0\,10^4$ cm^{-3} was adopted to extend between $1.0-1.8\,10^{17}$ cm. Beyond, there was a halo which was extending up to $3.0\,10^{17}$ cm and it was assumed to have two density components. One, of a density of 80 cm^{-3}, was filling 10% of the halo volume. The second one, filling the rest of the halo volume, had a density of 20 cm^{-3}. In course of time the whole nebula was uniformly expanding with a velocity linearly increasing from 15 km/s at the inner edge up to 30 km/s at the outer edge. After about 500 years the ionization front reached the trasition between the main dense nebula and the outer thin halo. In course of next 5 years the whole halo became ionized. Due to non-steady heating in the ionization front the electron temperature in the halo increased up to $2\,10^4$ K. The subsequent evolution resulted in a gradual cooling of the halo.

Figure 1 shows the evolution of the electron temperature as it would be "observed" from the [OIII] lines. The full curve corresponds to the "observations" across the centre of the nebular disc. This was almost entirely dominated by the

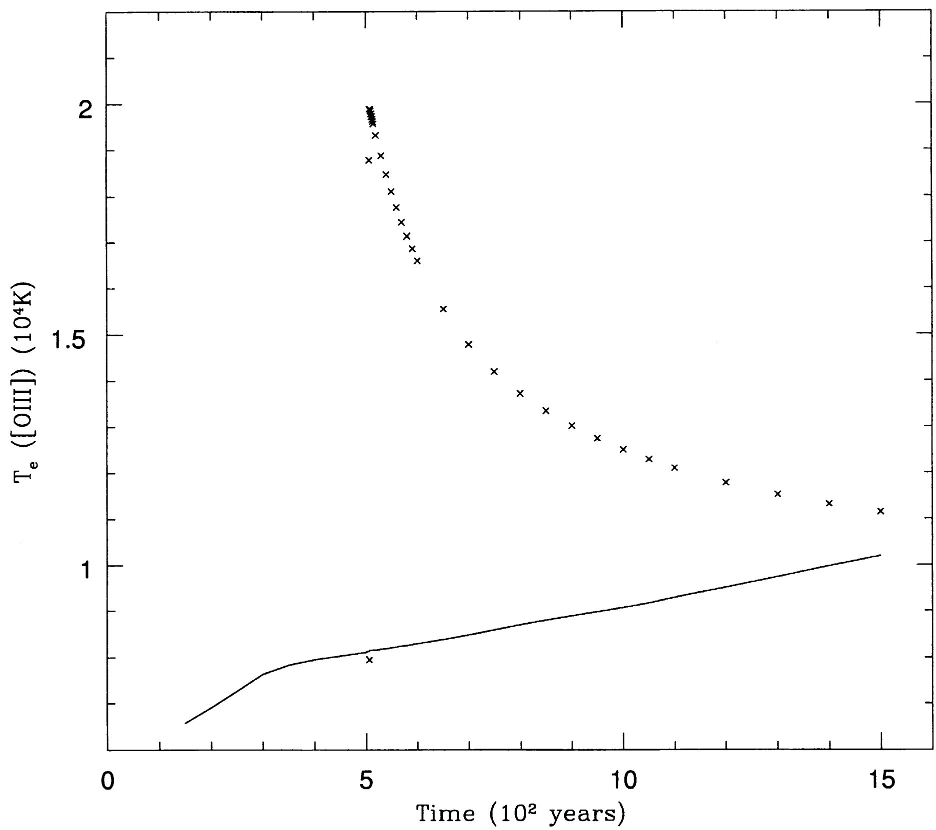

Figure 1. Evolution of the electron temperature "observed" from the [OIII] lines. Full curve - "observations" across the centre of the nebular disc. Crosses - "observations" in the halo.

main dense nebula. Crosses in Fig. 1 shows the results of the [OIII] "observations" in the halo, i.e. outside the bright inner nebula. The fast transition of the ionization front across the halo results in an abrupt rise of the "observed" halo temperature at 500 years in Fig. 1. As can be seen from Fig. 1, even 1000 years after its ionization the halo would still be observed in the [OIII] lines as hotter than the main nebula.

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