DYNAMICAL STRUCTURES OF PLANETARY NEBULAE - MODELS AGAINST OBSERVATIONS

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Abstract. Hydrodynamical calculations of Planetary Nebulae (PNe) over 25000 yrs of evolution which include timedependent effects of ionization as well as variable central stars winds and parameters consistent with stellar model calculations show a great variety of velocity and density structures which strongly deviate from the often assumed "homogeneous shells, expanding with constant velocities" (Marten & Schönberner, 1991, hereafter *MS*). By means of a static photoionization code we calculate the surface brightness in the 10 most prominent nebular emission lines for density structures of the model sequence "VS" as given by *MS*. The obtained radial emissivities are used together with the velocity and temperature structure of the ionized gas to calculate (thermally broadened) line profiles in order to derive "measured" expansion velocities. We compare the theoretical surface brightnesses with observations and demonstrate some difficulties in the interpretation of nebular expansion velocities, expansion distances and ages.

1. Detailed Model Analysis

The first nebular phase is characterized by completely ionization bounded models. Their radial structure is dominated by an ionization front which drives a density front into the neutral material. A typical velocity structure of a model during this "Ionization phase" is shown in Fig. 1a. The pressure of newly ionized matter accelerates the outer material near the ionization front and decelerates the inner nebular parts. However, an absolute expansion inwards is prohibited by the pressure of a hot bubble. Fig. 1b presents the corresponding normalized line profiles in [OII] λ 3729 and [OIII] λ 5007, calculated for an aperture with a diameter of 20% of the inner nebular rim which is placed at the PN center, so that we obtain double-peaked profiles. The peak separation which is often used as a measure of twice the expansion velocity is also given in Fig. 1b. It is obvious that lines from different ionization stages of the same element can be used to read off a velocity structure during this early phase of evolution, because these nebulae show clearly separated ionization zones: The emission in [OIII] mainly comes from the inner, low-density/low-velocity regions, while [OII] is generated in the higher-density, faster material farther outside (for the density structures of ionization bounded models see Fig. 6 of *MS*). Consequently, these PNe are also somewhat smaller in [OIII] than in [OII]. Furthermore, it is worth to notice that the measured peak separation can only give a *mean* velocity within the main emission region of the respective line, but at no time the minimum (5 km/sec) or maximum (25 km/sec) matter velocity.

As long as the star evolves with a constant luminosity, the growing energy input into the hot bubble dominates over its expansion cooling and causes an effective nebular compression. During this second, "Compression phase", the growing bubble pressure creates an inner region of high density while the ram pressure of the slow moving AGB-wind prevents the nebula from expanding too fast (Fig. 2a).

R. Weinberger and A. Acker (eds.), Planetary Nebulae, 315–318.

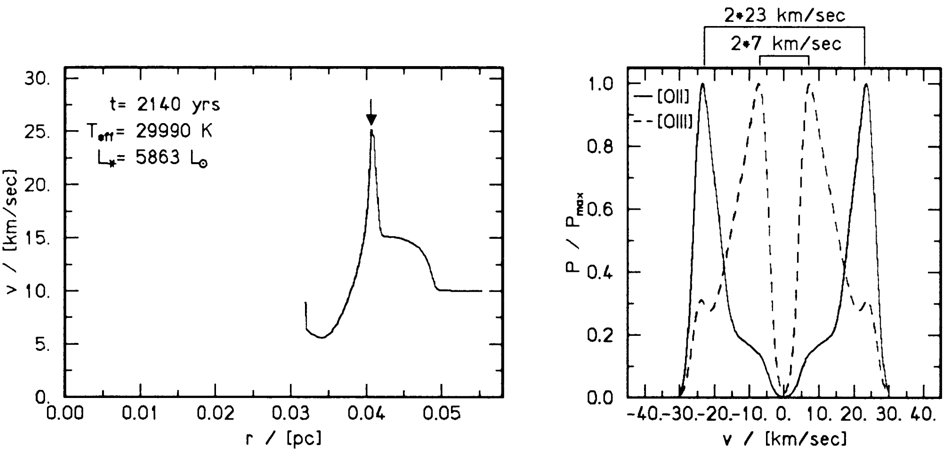

Fig. 1. Left panel (1a): Typical velocity structure of a nebular model according to *MS* during the "Ionization phase". The ionization front is marked by an arrow, model parameters are given in the upper left corner. Right panel (1b): Normalized line profiles in [OII] λ 3729 and [OIII] λ 5007 for the same model as measured through the nebular center (see text). The line intensities relative to $H_\beta = 100$ are 16.8 for [OII] and 11.1 for [OIII], respectively.

Fig. 2b presents the corresponding normalized surface brightnesses in the doublett [OII] $\lambda\lambda$ 3727,29 and in [OIII] λ 5007. Models during the "Compression phase" show a typical, often observed two-shell structure (Balick, 1987; Frank et al., 1990; Balick, 1992; Frank, 1992). The observed inner bright shell can be identified with the high-density, compressed nebular material, while the faint outer shell (with a sharp outer rim) is generated by the outer, low density nebular matter expanding into slow moving wind material. The image in [OII] shows a limb-brightening which has been called a "crown" by Franck et al. (1990). Fig. 2b demonstrates that the question of whether we observe a "crown" in an emission line or not is not only determined by the density but also by the detailed ionization structure of the nebula.

When the stellar luminosity drops, the mechanical wind power decreases by about three orders of magnitude within a short time. The work done by adiabatic expansion then dominates the energetics of the hot bubble, rapidly decreasing its pressure. Consequently, the velocity of the inner PN material decreases and the nebula enters into its "Late phase" where the relative shell thickness becomes larger again. The surface brightnesses in different nebular lines show more and more "centrally filled" objects which seem to have no central hole, like the (very) old planetaries PW 1, A 16 or A 30 .

2. Expansion velocities, Ages and Distances

MS found that R_N, the (outer) radius at 10% of the maximum surface brightness in H_β, is a rather good definition for the outer nebular rim. Therefore, we define the "nebular expansion velocity", $v(R_N)$, to be the radius change of the H_β-image per unit time: $v(R_N) = dR_N/dt$. This velocity is shown in Fig. 3, together with the maximum matter velocity, v_{max}, as well as the velocity at the maximum density,

https://doi.org/10.1017/S0074180900171062 Published online by Cambridge University Press

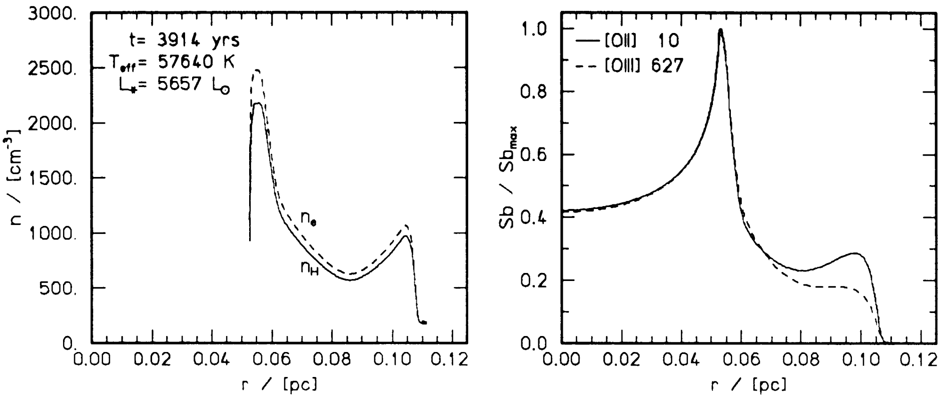

Fig. 2. Left panel (2a): Density structure of a nebular model according to *MS* during the "Compression phase". The model parameters are given in the upper left corner. Right panel (2b): Normalized surface brightness in [OII] $\lambda\lambda$ 3727,29 and [OIII] λ 5007 for the same model. Total line intensities (relative to $H_\beta = 100$) are given in the upper left corner.

$v(\rho_{max})$, in the resp. shells of the whole model sequence. The conspicuous discrepancy between v_{max} and $v(\rho_{max})$ around $t_{evol} = 3500$ yrs arises from the fact that our models during the early "Compression phase" show the largest velocities near the outer rim, where the densities are smallest. The contribution of these regions to the emission lines is so small that v_{max} can neither be determined from the HWHM nor from the peak separation of the line profiles. As the growing bubble pressure further compresses the nebula and the velocity gradients within the shell become less steep, the situation becomes better again. However, Fig. 3 also shows that the maximum measurable velocity in most cases is significantly smaller than the above defined nebular expansion velocity, since $v(R_N)$ represents the velocity of a *shock*! As long as the nebula is optically thick, the ionization front is trapped in a density front and the shock velocity is similar to the shown matter velocities. When the nebula becomes optically thin, the outer rim expands into pre-ionized AGB matter and the corresponding shock becomes faster than the post-shock matter. On the other hand, our models also warn us against a generalization of this result, since short evolutionary phases where $v(R_N)$ becomes even smaller than v_{max} cannot be ruled out in general. This may especially be the case when the maximum matter velocity is determined by a very high pressure of the hot bubble while at the same time $v(R_N)$ is determined by a relatively small ratio of the nebular to the AGB-wind density. In our sequence, $v(R_N)$ becomes comparable to v_{max} soon after the pressure of the hot bubble has decreased ($t_{evol} \approx 10000$ yrs) and it takes a further few 1000 yrs until the fast and dense matter from the inner rim has reached the outer rim, again increasing the shock velocity $v(R_N)$.

In some cases, the angular expansion of the nebular image per year together with a velocity derived from line profiles is used to derive expansion distances (Terzian, 1992). In our model sequence, this would lead to a systematic underestimation of the distance and an overestimation of the expansion age, t_{exp}, during most of the

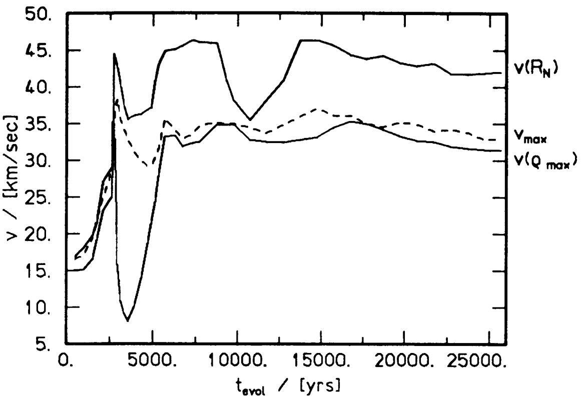

Fig. 3. Expansion velocity of the H_β-image, $v(R_N)$, maximum matter velocity, v_{max}, and matter velocity at the maximum density, $v(\rho_{max})$, within the PNe shells as a function of the model age.

nebular evolution, since the measurable matter velocities are too small compared to the expansion velocities. For example, for our final model at $t_{evol} = 25000\,$yrs ($R_N \approx 1\,$pc), we obtain $t_{exp} \approx 30000\,$yrs from $v_{max} = 33\,$km/sec.

3. Conclusions

The evolution of planetaries is a result of the competition between the pressure of a bubble of hot, shocked stellar wind gas, the pressure of the ionized nebular region and the ram pressure of the slowly moving AGB matter. During the whole lifetime of a PN, its structure is altered several times, so that it is impossible to derive a mass-loss history only from the present, "observed" radial density and velocity distribution. Dynamical calculations seem to be the only possibility to learn something about the past and future of a today observed object. For example, from these calculations it turns out that two shell planetaries can be explained *without* the need of a double mass-loss event. The analysis of dynamical PN calculations furthermore showed that expansion velocities and expansion distances might be systematically underestimated, while expansion ages of old planetaries are likely to be overestimated, apart from the difficulty that the observed nebular velocities are not constant, but are correlated with the stellar temperature (Heap, 1992). This is confirmed by dynamical calculations as well.

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