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The role of heat conduction to the formation of [WC]-type planetary nebulae

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Abstract. X-ray observations of young Planetary Nebulæ (PNe) have revealed diffuse emission in extended regions around both H-rich and H-deficient central stars. In order to also reproduce physical properties of H-deficient objects, we have, at first, extended our time-dependent radiation-hydrodynamic models with heat conduction for such conditions. Here we present some of the important physical concepts, which determine how and when a hot wind-blown bubble forms. In this study we have had to consider the, largely unknown, evolution of the CSPN, the slow (AGB) wind, the fast hot-CSPN wind, and the chemical composition. The main conclusion of our work is that heat conduction is needed to explain X-ray properties of wind-blown bubbles also in H-deficient objects.

Keywords. conduction, hydrodynamics, planetary nebulae: general

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In Steffen *et al.* (2008) we present time-dependent radiation-hydrodynamic models of PNe that include heat conduction at a solar (H-rich) composition. Extending the models to work with H-deficient compositions, we note that the general Fokker-Planck-based plasma theory of Spitzer (1962), to good accuracy, applies to both pure hydrogen and other chemical compositions. Heat conduction is modeled through a heat-flux term $\mathbf{q}$, which is written as a diffusion coefficient (D) multiplied with the temperature gradient, $\mathbf{q} = -D\nabla T$. The charge-dependent factor in D – i.e. $\varepsilon\delta_{\mathrm{T}}Z^{-1}$, where $\varepsilon(Z)$ and $\delta_{\mathrm{T}}(Z)$ are given in Spitzer & Härm (1953) – decreases modestly with increasing effective charge Z. Our more general tests with models that use typical H-deficient abundances show that $Z \leqslant 4.0$; the highest values are reached inside the hot wind-blown bubble in the PNe. Figure 1a shows that $D(Z)$, under H-deficient conditions, it is about a factor two smaller than in a pure hydrogen plasma of the same temperature, a rather insignificant decrease.

The treatment of the stellar evolution is a crucial issue in time-dependent models of the ionization structure in PNe. The quality of the models increases with more accurate predictions of the history of the slow wind (of the previous asymptotic-giant-branch stage), the fast wind, the central star (CSPN), and the abundances. The winds are characterized by their mass-loss rate, outflow velocity, and abundances; and the CSPN by its effective temperature (T_{eff}), luminosity, and mass. For H-rich compositions Pauldrach *et al.* (1988,2004) find that the mass-loss rate of the fast wind decreases with time. For CSPNe with a H-deficient composition, i.e. [WC] stars, empirical data show that the mass-loss rate instead increases with time (e.g. Leuenhagen *et al.* 1996; Fig. 1b). Simultaneously the fast-wind outflow velocity (v) is better fitted with a downscaled velocity-relation of Pauldrach *et al.* (1988), Fig. 1c. The fast-wind outflow velocity is the

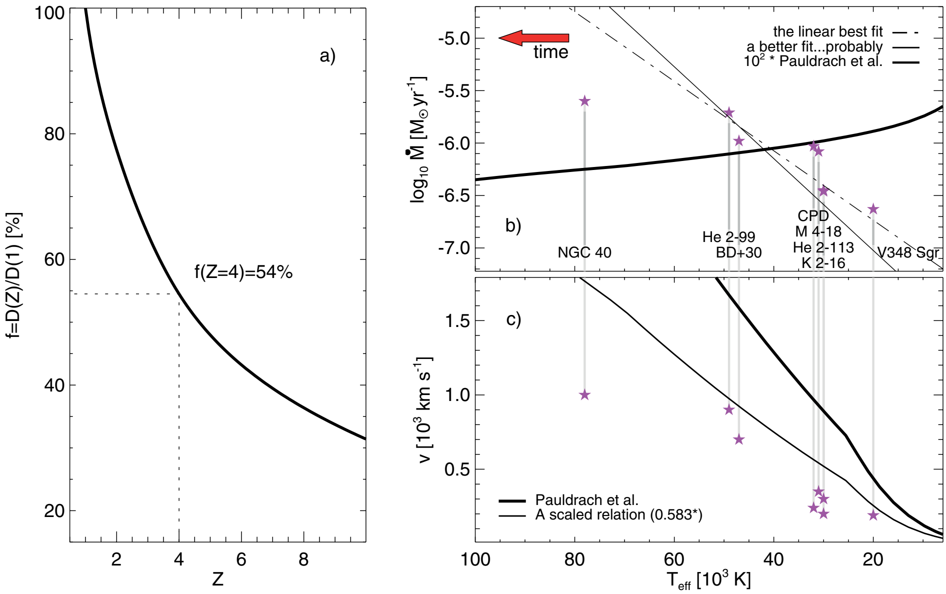

Figure 1. The diffusion-coeffient ratio $D(Z)/D(1)$ is shown in panel **a**. The fast-wind mass-loss rate $\dot{M}(T_{\rm eff})$ (velocity v) of Pauldrach *et al.* is shown in panel **b** (**c**) together with linear fits (a scaled relation) of measured data of [WC] stars.

most decisive factor to the formation of a hot wind-blown bubble. Our studies with [WC] stars require an outflow velocity of about $v = 1000\,{\rm km\,s^{-1}}$ to form a bubble.

Without heat conduction a hot wind-blown bubble forms (eventually) between the shock and the contact discontinuity, regardless of the chemical composition of the winds. The bubble is in this case very hot, the electron temperature $T_{\rm e} \geqslant 10^7$ K, which is also much higher than what X-ray observations show. With heat conduction heat is transported out of the bubble, causing an increased rate of evaporation, which in turn leads to a lower temperature in the bubble. In this case $T_{\rm e} \simeq 10^6$ K. The bubble structure is also different, most notably there is a strong temperature gradient inside the bubble and, depending on age, the chemical discontinuity may be located somewhere inside the bubble. No bubble seems to form if both the fast and the slow winds are H-deficient. It should be possible to form a bubble also if the heat-conduction flux is lowered by magnetic fields. Although, the temperature inside the bubble will then increase.

This theoretical work will be presented in more detail in Sandin *et al.* (in prep.). Thereafter we plan a follow-up study on matching a models with observations of BD+30°3639.

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