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Dynamics of [WR] Planetary Nebulae

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Abstract. The formation of PNe around [WC] stars is modelled with a numerical hydrodynamics code. It is found that the PN around [WC] are expected to expand faster, and be more turbulent. It is shown that the observed lack of differences with 'normal' PNe, can have implications for models of the origin of asphericity in PNe.

1. Introduction

An estimated ~ 7% of Planetary Nebulae (PNe) have central stars with a [WR] type spectrum. These stars have hydrogen-deficient fast winds, and substantially higher mass loss rates than 'normal' central stars. The most abundant elements in their stellar atmospheres are helium and carbon, therefore the spectral type is said to be [WC].

In this paper we investigate whether the [WC] properties of the wind influence the formation of the surrounding PN. A related question is whether comparing [WC]-PNe and normal PNe can teach us something about the formation process of PNe.

2. Properties of [WC] stars and their nebulae

A review of the properties of [WC] central stars can be found in the contribution of Hamann in this volume, and in Koesterke (2001). The most important properties of [WC] CSPNe are their high mass loss rates, typically a factor 10 higher than 'normal', and the abundances, which can be characterized as 50% He, 40% C, and 10% O (by mass).

The contribution of Herwig in this volume reviews the proposed origins for the [WC] phenomenon. For the models in this paper we will assume that the star evolved off the AGB with typical [WC] abundances.

The properties of the nebulae around [WC] stars have been most recently been reviewed by Górny (2001), and spectroscopic studies have been done by Peña, Stasińska & Medina (2001) and Acker et al. (2002). Comparing general properties such as galactic distribution, abundances, and morphologies, Górny (2001) found no systematic differences between [WC]-PNe and normal PNe. This shows that the [WC] phenomenon is not linked to an initial mass range, nor can be traced while the star is still on the AGB. The spectroscopic studies show that all [WR]-PNe have quite wide nebular emission lines which can only be fitted if a turbulent velocity component is used in addition to the thermal

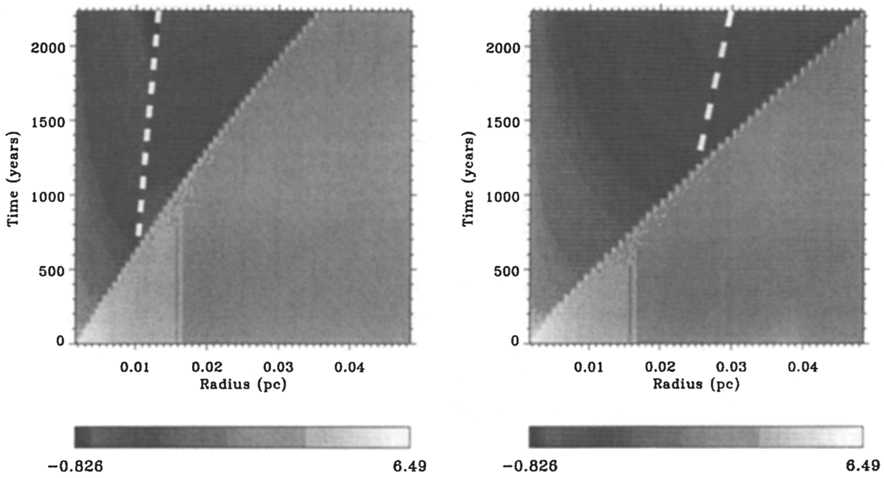

Figure 1. Gray scale plots of the logarithm of the gas density as a function of position (horizontal axis) and time (vertical axis). Left: a fast wind with solar abundances. Right: one with [WC] abundances. The position of the inner shock is indicated with a dashed white line.

component. Górny (2001) also concluded that the expansion velocity of [WC]-PNe is systematically higher than for normal PNe.

3. Numerical Method

In order to model the effect of the H-deficiency of the stellar winds, one needs a numerical method which describes the detailed physical processes in the gas in a species-dependent way. Raga, Mellema & Lundqvist (1997) described an approach for dealing with non-equilibrium cooling and ionization in hydrodynamic simulations. In the new method used here, we follow their general ideas, but include *all* ionization stages of H, He, C, N, O, and Ne, and allow all ions to contribute to the electron density. Photo-ionization is not currently taken into account. Details of the method can be found in Mellema & Lundqvist (2002).

4. Simulation of a [WC] wind bubble

We ran two one-dimensional simulations, simulating a spherical wind bubble formed by a time-dependent wind. Simulation A contains solar abundances throughout, simulation B uses [WC] abundances for the wind, and solar abundances for the environment.

The simulations were set up to resemble the ones by Dwarkadas & Balick (1998). The environment is taken to be a slow AGB wind with a velocity of $v_{\rm sw}$=10 km s^{-1}, and a mass loss rate of $\dot{M}_{\rm sw}$ = 10^{-5} $M_\odot$ yr^{-1}, the fast wind evolves from slow (25 km s^{-1}) to fast (2000 km s^{-1}) in 3000 years. The evolution is according to a power law

$$v_{\rm fw} = v_{\rm fw,initial}\,(1 + t/\tau)^{1.5} \qquad (1)$$

As the wind velocity increases, the mass loss drops so that $\dot{M}_{\rm fw} v_{\rm fw}$ remains constant, as is expected for a radiation driven wind at constant luminosity. For simulation A the initial mass loss rate is $10^{-6}\ M_\odot\ {\rm yr}^{-1}$, for simulation B it is $10^{-5}\ M_\odot\ {\rm yr}^{-1}$.

As explained by Kahn & Breitschwerdt (1990), such a time-dependent wind will produce a bubble which is initially *momentum-driven*, and then makes a transition to *energy-driven*. In the momentum-driven bubble, the shocked stellar winds cools efficiently, and the inner shock lies just inside the swept up shell (the PN). The expansion is driven by the momentum in the fast wind. For higher wind speeds, the cooling processes are less efficient, and the inside of the bubble will fill up with hot, shocked, fast wind gas, the 'hot bubble'. The inner shock will distance itself from the swept-up shell. Now it is the pressure (energy) of the hot bubble which drives the expansion of the bubble.

Kahn & Breitschwerdt (1990) analytically estimated this transition to happen at wind speeds of 150–200 km s^{-1}, a range conmfirmed in the more detailed numerical simulations of Mellema (1994) and Dwarkadas & Balick (1998). Since this number depends on the cooling processes in the fast wind, it is expected to be higher for [WC] winds.

Figure 1 shows the results of the two simulations. The evolution of the logarithm of the density is shown as a function of time and position, so that it is easy to trace the position of the inner shock, contact discontinuity and outer shock as a function of time. The transition from momentum-driven to energy-driven is marked by the separation of the inner shock from the contact discontinuity. In simulation A this happens at $t = 650$ years, at which point the fast wind has a velocity of 180 km s^{-1}, in accordance with what was found before. In the [WC] wind simulation the transition happens much later at $t = 1250$ years, for a fast wind velocity of 550 km s^{-1}. This is caused by the much higher cooling rates in the extremely metal-rich [WC] wind.

Figure 1 also shows that the expansion velocity of the PN is higher in the case of the [WC] wind. At the end of the simulation, the expansion velocity is 17 km s^{-1} in simulation A, and 25 km s^{-1} in simulation B. This is due to the higher mass loss rates in the [WC] wind.

5. Discussion

5.1. Effects of the later transition

As was shown by Dwarkadas & Balick (1998), young PNe are sensitive to the non-linear thin shell instability while the bubble is momentum-driven. The fact that the [WC] bubble remains momentum-driven for a longer time allows this instability to operate for a longer time. This can then explain why [WC]-PNe are observed to contain a turbulent velocity component: the PNe suffered from the instability longer. An added effect may be the variablility of the [WC] winds (Acker et al. 2002), although there are no comparable studies for normal fast winds.

A second effect of the later transition is that asphericities in the fast wind have more time to imprint themselves on the PN. Only in the momentum-driven phase can an aspherical fast wind efficiently produce an aspherical PN. The lack of systematic differences between the morphologies of normal and [WC]-PNe would then indicate that an aspherical post-AGB wind is not responsible for producing aspherical PNe.

5.2. Effects of the higher mass loss rate

As is easily understood, a higher mass loss rate in the fast wind leads to a higher expansion velocity of the nebula, as found in the simulations. It was claimed to be found in the observations too (Górny 2001), although Acker et al. (2002) now claim this result to be spurious. This aspect needs some more study.

Interestingly, higher mass loss rates may affect the magnetic shaping scenario for aspherical PNe of Chevalier & Luo (1994) (see the contribution of Garcia-Segura for more details). The efficiency of this process is given by the parameter σ

$$\sigma = \frac{B_{\rm star}^2 R_{\rm star}^2}{\dot{M} v_{\rm fw}} \left(\frac{v_{\rm rot}}{v_{\rm fw}} \right)^2 \qquad (2)$$

This implies that for stars with higher mass loss rates, magnetic shaping will be less efficient. In other words, [WC]-PNe would be rounder than normal PNe. Since no systematic differences in morphology have been found, this could indicate that magnetic shaping is not the dominant process.

6. Conclusions

We have shown that PNe around [WC] are expected to be more turbulent, and expand faster than 'normal' PNe. The observed lack of systematic morphological differences between [WC]-PNe and normal PNe can perhaps be used to test models for the origin of asphericity in PNe.

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