RevMexAA (Serie de Conferencias), **15**, 41–43 (2003)

Winds, Bubbles, & Explosions: A Conference to Honour John Dyson. Pátzcuaro, Michoacán, México, 9-13 September 2002. Editors: S. J. Arthur & W. J. Henney

STELLAR WIND BUBBLES: H-DEFICIENT STARS AND X-RAY SPECTRA

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RESUMEN

Presentamos modelos numéricos unidimensionales simplificados de burbujas formadas por vientos estelares (SWB) para investigar dos aspectos: el efecto de los vientos deficientes en hidrógeno, tales como se observan en las estrellas centrales tipo [WR] de nebulosas planetarias y las estrellas Wolf-Rayet masivas, y el espectro de rayos-X que producen las SWB. En el caso de los vientos pobres en hidrógeno, encontramos que el enfriamiento adicional debido a las extremadamente altas abundancias de metales influye en la estructura y evolución de las SWB, aunque en mayor parte se mantienen impulsadas por energía. En el caso de los espectros de rayos-X, encontramos que un modelo de SWB estándar no puede explicar los espectros observados y se requiere de un efecto físico adicional. Demostramos que la conducción térmica con una eficiencia baja podría ser el efecto necesario.

ABSTRACT

We present simplified one-dimensional numerical models for stellar wind bubbles (SWB), investigating two aspects: the effect of H-deficient winds, such as observed in [WR]-type centrals stars of planetary nebulae (PN) and massive Wolf-Rayet stars (WR), and the X-ray spectra produced by SWBs. For the H-deficient winds, we find that the extra cooling caused by the extremely high metal abundances influences the structure and evolution of their SWBs, although they remain mostly energy-driven. For the X-ray spectra we find that a standard SWB model cannot explain the observed spectra, and some extra physical effect is needed. We show that thermal conduction with low efficiency can be this effect.

Key Words: **HYDRODYNAMICS — ISM: BUBBLES — PLANETARY NEBULAE: GENERAL — STARS: AGB AND POST-AGB — STARS: WOLF-RAYET — X-RAYS: ISM**

1. H-DEFICIENT STARS

Both low- and high-mass stars are sometimes able to strongly change the abundances in their atmospheres. When this leads to a severe reduction of the hydrogen abundance, luminous, hot stars often become so-called Wolf-Rayet stars. These stars are characterized by a strong and fast stellar wind, which is so dense that even at optical wavelengths the photosphere lies inside the wind. In the case of massive stars we call these stars WR stars, and they probably form the end stage in the evolution of massive stars. In the case of low-mass stars they are denoted [WR] stars, and form a subclass ($\sim$ 5 to 10%) of central stars of planetary nebulae (PNe). If carbon is highly abundant, the spectroscopic nomenclature refers to WC or [WC] stars. All low-mass [WR] stars are [WC]; in the case of high-mass WR stars, there are also WN (N-rich) and WO (O-rich) types.

All types of WR stars produce stellar wind bubbles. In the case of [WC] stars these are the PNe, in the high-mass case they called ring nebulae (RNe). In the first part of this contribution we look at how the H-deficient character of the stellar atmosphere, and hence the stellar wind, makes a difference to the structure and evolution of these nebulae. A more complete description of the simulations and the effects outlined in this contribution can be found in Mellema & Lundqvist (2002).

2. BASIC PROPERTIES OF WIND BUBBLES

A simple description of a stellar wind bubble is the so-called three shock pattern, in which the bubble consists of three zones, expanding into an environment: (1) a freely expanding stellar wind zone, (2) a high temperature, shocked stellar wind zone, (3) swept up material from the environment. Below we will refer to these numbers.

The extent of zone 2 depends on the efficiency of the cooling in that zone. If cooling is very efficient, zone 2 is almost non-existent, and zone 1 extends nearly to zone 3. In this case, the ram pressure of the stellar wind drives the expansion of the bubble, and we call it a momentum-driven (M-driven, sometimes also called radiative) bubble. If cooling is inefficient, zone 2 is extended and its high thermal pressure is the driving agent of the bubble expansion. Such a bubble is called energy-driven (E-driven, sometimes called adiabatic, or non-radiative). These two cases are the extremes; intermediate cases also exist.

The efficiency of cooling depends on the density and velocity of the stellar wind. High density and low velocity winds are more likely to be M-driven.

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However, the cooling does also depend on the abundances in the stellar wind. Specifically, metals are efficient coolants, and the high metal abundances (1000 times Solar) in WR winds can therefore be expected to have an effect. It is this effect we wish to study.

An often-used observational way to test whether a SWB is M-driven or E-driven is to compare the momentum and kinetic energy in the swept-up shell (zone 3) with the estimated total momentum and kinetic energy input from the stellar wind. The ratio of momenta is called π, that of kinetic energies ϵ, see e.g., García-Segura & Mac Low (1995). A value of approximately one for π is expected for a M-driven bubble.

3. CONSTANT STELLAR WIND

To determine the usefulness of the ratios π and ϵ we ran simulations of a stellar wind of constant mass-loss rate and velocity, running into a slowly expanding environment, representing a previous mass-loss phase—that of a luminous blue variable or red supergiant in the case of RNe, or of an asymptotic giant branch (AGB) star in the case of PNe. For all the cases tested we find that the values of ϵ and π are not good measures of the character of the SWB. Although all SWBs are clearly E-driven with a volume of hot gas inside them, the values of π and ϵ lie in between the theoretically expected values for purely E-driven and purely M-driven, showing that π and ϵ are of very limited use. None of the model WR SWBs were found to be M-driven, even though observational claims for M-driven RNe exist (Treffers & Chu 1982; Cappa et al. 1996). Since these claims are based on the "observed" values of dubious π and ϵ ratios, we conclude that real WR SWBs are not M-driven.

4. EVOLVING STELLAR WIND

To determine the influence of the WR abundances on the evolution of the bubble, we ran simulations in which the velocity of the stellar wind goes up, and the mass-loss rate goes down with time. This is a simplified model for the evolution from an AGB star towards the PN phase, as introduced by Kahn & Breitschwerdt (1990) and also used by Dwarkadas & Balick (1998). In such a model a transition from M-driven to E-driven occurs since with time the stellar wind velocity goes up, and its density goes down, making cooling less and less efficient. Previous analytical and numerical models found that this happens around a wind velocity of $\sim 150\,\mathrm{km\,s^{-1}}$. We reproduce this result when using Solar abundances, but find a much higher transition velocity in case of [WC] abundances, $\sim 500\,\mathrm{km\,s^{-1}}$. This shows that the internal structure of young [WC]-PNe is likely to differ from normal PNe. If post-AGB winds were aspherical, a longer M-driven period would expose the PNe longer to the aspherical ram pressure of the wind. This would shape the PNe, leading to more aspherical (or differently shaped) [WC]-PNe. This is not observed (Górny 2001). What is observed is that the line shapes in [WC]-PNe are broadened, probably through a high turbulent velocity component (Acker et al. 2002). This can be understood in terms of our models by realizing that during the M-driven phase, the PN shell is subject to the non-linear thin shell instability (Vishniac 1994). Clearly a longer M-driven phase will give this instability more time to seriously affect the PN shell. An added effect may be that even when later a zone 2 develops during the E-driven phase, it will have a smaller extent in [WC]-PNe than in normal PNe, allowing the effects of the highly variable winds from [WC] stars to more easily reach the PN shell.

5. X-RAY SPECTRA FROM WIND BUBBLES

Zone 2 of a SWB contains a hot plasma, and will produce X-ray photons. The *Chandra* X-ray observatory has managed to measure these in a number of PNe and RNe and determine the spectrum (see e.g., the review by Chu, Gruendl, & Guerrero 2003). Modeling this spectrum with a single temperature plasma gives typical temperatures of order a few million Kelvin. This is in contrast with the expected values, which are at least a factor 10 higher, as derived from the post-shock temperature of the shocked stellar winds.

Using a simple one-dimensional hydrodynamic model for a spherical SWB, it is possible to derive a more realistic expected X-ray spectrum. A hydrodynamic model produces a range of temperatures and densities, and it is not obvious that this will produce a spectrum which is well described by a single-temperature model. Also, a hydrodynamic model containing non-equilibrium ionization may show that the ionization in the low density zone 2 is not in collisional equilibrium throughout.

Figure 1*a* shows an X-ray spectrum calculated from a hydrodynamic model. Although it is dominated by emission from the range 0.5 to 1.0 keV, the high energy tail is inconsistent with the observed spectra, showing that there is indeed discrepancy between the models and the observations.

Three effects could modify the X-ray spectrum and make it softer: (1) non-equilibrium ionization, (2) thermal conduction between zone 3 and zone 2, (3) mass loading by dense clumps which enter zone 2.

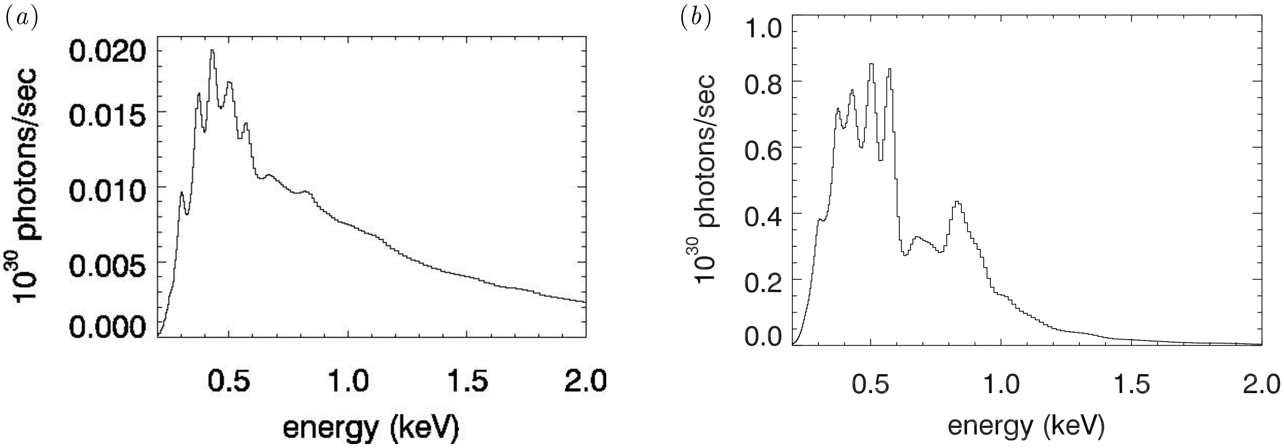

Fig. 1. Synthesized X-ray spectra calculated from the density, temperature and abundance distribution of a simulation of two interacting winds: (*a*) without thermal conduction; (*b*) with 1% efficient thermal conduction. The parameters of the winds were: $\dot{M}_{\rm AGB} = 2 \times 10^{-5}\,M_\odot\,{\rm yr}^{-1}$, $v_{\rm AGB} = 10\,{\rm km\,s}^{-1}$, $\dot{M}_{\rm fast} = 10^{-7}\,M_\odot\,{\rm yr}^{-1}$, $v_{\rm fast} = 2000\,{\rm km\,s}^{-1}$. The H I column density between us and the PN is taken to be $9 \times 10^{20}\,{\rm cm}^{-2}$. The spectra are smoothed to approximate the resolution of the *Chandra* ACIS spectral resolution, but were not convolved with the instrumental response function.

Here we test the first two options. The model contains a non-equilibrium ionization calculation for N, O, and Ne, elements which produce the dominant lines in the observed X-ray spectra. We find that these elements are not substantially out of equilibrium, and therefore option 1 seems not to be the explanation for the discrepancy.

We ran an identical model, but this time adding the effect of thermal conduction through hot electrons, which makes material from zone 3 (the nebular shell) "evaporate" into zone 2, raising its density and lowering its temperature. We find that thermal conduction at a level of 1% of its nominal value, is already capable of reproducing the observations (Fig. 1*b*). This is relevant since even a weak magnetic field will inhibit thermal conduction. These results show that thermal conduction operating at 1% of the surface of the interface between zones 2 and 3, in combination with efficient mixing within zone 2, are sufficient to explain the observed X-ray spectra. In the case of a turbulent magnetic field this could be the case. In the case of a more structured magnetic field, there may even be effects on the structure of the SWB, see Zhekov & Myasnikov (2000).

Option 3 is also an attractive explanation. Observations of the nearby Helix nebula show that small condensations indeed end up in zone 2, and seem to have raised its density and lowered its temperature, to the point that no X-rays have been detected from the Helix nebula. Looking at the four PNe for which X-ray spectra exist, there appears to be a trend of softer spectra with age. This supports mass loading as an explanation. We will investigate this option in future work.

6. CONCLUSIONS

1. SWBs around H-deficient stars with wind velocities above $1000\,{\rm km\,s}^{-1}$ are E-driven. The parameters π and ϵ are not well suited to discriminate between E-driven and M-driven SWBs.

2. SWBs around H-deficient stars with increasing wind speeds remain M-driven longer than the equivalent stars with Solar abundances. This leads to more aspherical SWBs if the wind is aspherical, and more turbulent SWBs through the non-linear thin shell instability.

3. Low efficiency ($\sim 1\%$) thermal conduction is sufficient to explain the observed X-ray spectra of PNe.

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