X-Ray Emitting Gas in Circumstellar Nebulae

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Abstract. Recent high-resolution 2D radiation-hydrodynamic numerical simulations of the formation and evolution of hot bubbles around evolved stars are described. The simulations take into account the evolution of the stellar parameters such as ionizing photon rate, wind velocity and mass-loss rate for a range of initial stellar masses. For low-mass stars, a planetary nebula with a lifetime of a few thousand years forms around the central hot star, while for massive stars the result is a Wolf-Rayet nebula, which has a lifetime of tens of thousands of years. In both cases, instabilities in the fast wind-slow wind interaction zone produce clumps and filaments in the swept-up shell of nebular material. Turbulent mixing and thermal conduction at the corrugated interface can produce quantities of intermediate temperature and density gas between the hot, shocked wind bubble, and the swept-up photoionized nebular material, which can emit in soft, diffuse X-rays. Sampling of the resultant theoretical spectra helps to make meaningful comparisons with recent observations of planetary nebulae.

1. Introduction
Circumstellar nebulae are formed when a fast stellar wind sweeps up gas that was expelled during a previous stage of the star’s evolution and the dense, compressed shell is then photoionized by energetic photons from the hot central object. Although optical nebulae characterize this interaction, interior to the dense, photoionized shell is a bubble of hot, shocked fast wind plasma, which, in principle, should be observable in X-rays.

In general terms, after core hydrogen burning is finished, a star leaves the main sequence and its subsequent evolution proceeds rapidly. The star moves to the red on Hertzsprung-Russell diagram and expels its hydrogen-rich envelope before heading to the blue as the hot helium-rich core becomes exposed. This process occurs for both low-mass ($M_{\text{init}} < 8M_\odot$) and very high-mass ($M_{\text{init}} > 30M_\odot$) stars. For low-mass stars, the end result is a planetary nebula (PN), while the very high-mass equivalent is a Wolf-Rayet nebula (WRN).

In both low-mass and very high-mass scenarios, the details of the mass loss immediately prior to the fast wind stage are crucial for the formation and appearance of the nebula. For low-mass stars, the evolution from the asymptotic giant branch to the white dwarf cooling track is reasonably well understood. Whatever the initial mass of these stars ($< 8M_\odot$), the final mass must be less than a Chandrasekhar limiting mass ($\sim 1.4M_\odot$) and so the progenitor can lose more than half its mass through thermal pulses and superwind in the final stages. In fact, only stars with initial mass less than about $3.5M_\odot$ form observable PN; higher progenitor masses lead to objects with optically thick envelopes.

The late stages of very high-mass stellar evolution are less well understood. Stellar winds are important throughout the lifetime of these stars, even on the main sequence. Stellar rotation
promotes mixing in the stellar interior, which enhances mass loss at the surface and thus extends the main sequence lifetime of these objects. A massive star will lose half its mass in dense, slow winds during a red supergiant (RSG) or luminous blue variable (LBV) stage.

The timescales for PN before the fast wind switches off and the star settles onto the white dwarf cooling track are very short, typically less than 10,000 yrs and the size scales are small < 0.5 pc. However, PN are quite numerous and reasonably bright objects. WRN are much larger > 3 pc and because there is still ongoing fusion in the hot central object, the lifetimes are much longer. However, observable WR wind-blown nebulae are few in number and they are lower luminosity than PN because, being such extended objects, the densities are lower.

Hot gas is expected to fill both PN and WRN but X-ray observations present a puzzling picture. The CHANPLANS program is a statistically significant study of X-ray emission from PNe within 1.5 kpc of the Sun, which to date has detected 30% of target PNe in diffuse X-rays [1, 2]. On the other hand, only 4 WRN have been detected in X-rays [3, 4, 5]. Curiously, the derived X-ray temperature of the emitting gas for all these objects is in the narrow range 1–3 × 10⁶ K, even though the stellar wind velocities would suggest that the hot, shocked gas should have temperatures in excess of 10⁷ K.

In this paper, we discuss numerical models of PN and WRN and the formation and evolution of hot bubbles in these objects. We examine the X-ray properties of the hot gas and possible reasons for the apparently low temperatures.

2. Formation of Circumstellar Nebulae

![Figure 1](chart.png)

**Figure 1.** Evolution of fast stellar wind parameters for evolved, low-mass stars of 4 different progenitor masses. Left panel: mass-loss rate. Right panel: wind velocity. The red shaded area represents the AGB stage, while the blue shaded area starts once $T_{\text{eff}} > 10^4$ K.

Circumstellar nebulae are shaped both by the details of the mass-loss prior to the onset of the fast wind, as well as by the acceleration timescale of the fast wind.

For low-mass progenitors near the top of the asymptotic giant branch (AGB), the superwind is characterized by slow, dense ($v_{\infty} < 30$ km s⁻¹, $\dot{M} \sim 10^{-4} M_\odot$ yr⁻¹) episodic mass loss due to radial pulsations in the expanded stellar envelope. The ejected material forms multiple shells around the star. The transition to central star of a PN is accompanied by a large reduction in the mass-loss rate ($\dot{M} \sim 10^{-8} M_\odot$ yr⁻¹) and corresponding increase in the stellar wind velocity, which can reach > 1000 km s⁻¹ on a timescale of a thousand years (see Figure 1). The stellar ionizing photon rate follows a similar trend to the mass-loss rate and drops off steeply. PN are only detectable for a few thousand years because the expansion means the gas becomes very diffuse and also the photons illuminating the nebula drop off. The effective temperature of the star is a good observational proxy for time during this stage.
The evolution of very massive stars depends very much on the ingredients of the stellar evolution code and different groups of researchers have produced very different results. For example, Figure 2 shows results for post-main-sequence mass loss for a progenitor $40 M_\odot$ star obtained by the Geneva group, where the difference between the two models is that one assumes an initial rotation velocity of $300 \text{ km s}^{-1}$ (at the equator) for the star, while the other model has no rotation [6]. The mass-loss rates and timescales are widely different between the models. The intensity and duration of the slow wind phase determines how far away from the star and how dense the shells of material swept up by the fast wind can be.

Figure 2. Mass-loss rate for post-main-sequence evolution of a $40 M_\odot$ star obtained from Geneva Group stellar evolution models with (MM-ROT) and without (MM) rotation [6]. Shaded areas indicate slow, dense wind phase.

3. Numerical Simulations

We have performed numerical simulations in 1D spherical symmetry and 2D axisymmetry of the interaction of the time-evolving fast stellar wind with the circumstellar medium sculpted by previous slow, intense mass-loss episodes for both high-mass and low-mass stars [7, 8, 9, 10]. These calculations include the radiative transfer of the time-varying ionizing photons from the central star. Radiative cooling with appropriate chemical abundances is taken into account. The calculations are performed both with and without thermal conduction, which affects the density and temperature distributions at the edge of the hot bubble. Conduction has been postulated as a means of reducing the temperature in the hot bubble in order to achieve the temperatures indicated by X-ray observations [11, 12]. Our conduction models and pure hydrodynamic models are taken to represent the two extremes of behaviour. Magnetic fields in PN are extremely weak but conduction by thermal electrons will be inhibited in the direction perpendicular to the field lines; the real behaviour could be expected to fall somewhere in between our 2 extremes.

The initial conditions for these calculations are set by the evolution in the slow, dense wind stage. For full details of the code, see [7, 8, 10].

3.1. Planetary Nebulae

We start with PN, in particular, the results for a $1.5 M_\odot$ initial mass star. Figure 3 shows the number density of the ionized gas and temperature distribution after 7400 yrs of post-AGB evolution during the 2D axisymmetric simulation. Results are shown for simulations with and without thermal conduction. Instabilities develop early in the interaction between the fast wind and the earlier slow, dense wind material, leading to the formation of clumps and filaments in the swept-up shell. Photoevaporated flows from the heads of the inward-pointing filaments carve out cavities in the interior of the bubble, and interacting non-radial flows generate turbulent mixing regions. Heat diffusion by electrons from the hot bubble into the surrounding swept-up shell evaporates cold, dense material into the bubble interior. Both processes lead to mixing at the interface, which has a large surface area due to the corrugations.

Figure 4 shows the density and profiles of 1D spherically symmetric simulations of the same PN, together with angle-averaged profiles obtained from the 2D axisymmetric simulations where
Figure 3. Number density in the ionized gas and temperature distribution after 7400 yrs of post-AGB evolution. Top panels: simulation without conduction. Bottom panels: simulation with thermal conduction.

all simulations have the same numerical resolution and input physics. It can be seen that thermal conduction reduces the temperature throughout the hot bubble and evaporation raises the density close to the contact discontinuity. On the other hand, instabilities do not occur and there are no turbulent, hydrodynamic mixing regions. The density of the swept-up shell of the 1D simulations is higher, and the shell is narrower. In this 1.5\(M_\odot\) case, however, the shell remains optically thin. In the 2D simulations, opacity differences in the clumpy unstable shell lead to ray patterns in the photoionized envelope gas beyond due to shadowing effects.

The simulations proceed until the stellar wind mechanical luminosity falls off and back-filling occurs in the nebula as the photoionized material expands inwards.

3.2. Wolf-Rayet Nebulae

The essence of a WRN is the interaction of a fast wind with a dense circumstellar medium produced during the red supergiant (RSG) or luminous blue variable (LBV) immediately preceding the transition to Wolf-Rayet star. Although the exact details vary, the scenario is the same regardless of the stellar evolution model adopted. The main difference is the distance the slow wind material has managed to travel from the star before the fast wind switches on. The interaction consists of an initial stage, in which the fast wind drives a shock into the dense circumstellar medium, which sweeps up a dense shell of material that quickly becomes unstable
Figure 4. Density and temperature profiles of 1D spherically symmetric simulations (thin lines — with conduction; dashed lines — without conduction) together with angle-averaged profiles from 2D axisymmetric simulations (thick lines) of planetary nebula evolution for a 1.5\textit{M}_\odot initial mass star. Left panel: 2D simulation without conduction. Right panel: 2D simulation with thermal conduction. All simulations shown after 7400 years of post-AGB evolution.

Figure 5. Left panel: logarithm of temperature for a typical Wolf-Rayet nebula simulation (without thermal conduction) after 20,000 yrs of evolution. Right panel: value of scalar tracing fast-wind material (scalar value 0) and ambient material (scalar value 1).

(initially due to the thin shell instability and then the shadowing instability) and breaks up into clumps and filaments. Later, the ragged swept-up shell interacts with the edge of the
circumstellar material and breaks out into the low-density interstellar medium beyond. The size scales and time scales of WRN are both about an order of magnitude greater than those of PN. The mass-loss rate of Wolf-Rayet stars is at least 3 orders of magnitude greater than that of the central stars of planetary nebulae, and so the fast wind material in WRN will have a relatively more important contribution to the X-ray emission of the diffuse gas.

Figure 5 shows the temperature distribution in a typical simulation, together with the distribution of a scalar, which has value 0 in the fast wind and value 1 in the ambient material. The initial condition was a spherically symmetric density distribution generated by a uniform, slow, dense wind from the RSG stage that ejected a total of $15M_\odot$ of material over 200,000 yrs. The wind speed of 15 km s$^{-1}$ puts the rim of the dense circumstellar material at a distance 2.3 pc from the star. The fast wind has a constant velocity of 1600 km s$^{-1}$, a mass-loss rate of $7 \times 10^{-5}M_\odot$ yr$^{-1}$, and the ionizing photon rate is $2.6 \times 10^{49}$ s$^{-1}$. The simulation is shown 20,000 yrs after the onset of the fast wind. The clumps and filaments are the result of instabilities in the swept-up shell, which have then collided with the dense rim of the circumstellar material and broken out into the diffuse, main-sequence wind bubble beyond.

4. X-ray Emission

The X-ray emission corresponding to the hot bubbles produced in the simulations can be calculated easily using the idea of Differential Emission Measure (DEM) if we assume that the planetary (or Wolf-Rayet) nebula is optically thin to X-ray photons.

4.1. Differential Emission Measure

In this work, we define the Differential Emission Measure, $DEM(T_b)$, of gas in temperature bin $T_b$ of width $\Delta T_b$ as follows:

$$DEM(T_b) = \sum_{k,T_k \in T_b} n_H n_e \Delta V_k,$$

where the summation is over all computational cells, $k$, of volume $\Delta V_k$. The hydrogen number density and electron density are $n_H$ and $n_e$, respectively. We consider 100 temperature bins equally spaced in $\log T$ between $\log T = 5.0$ and $\log T = 9.0$ with bin width 0.04 dex.

Figure 6 shows the DEM histograms at four different times for the simulations described in Section 3. In each profile, the maximum temperature corresponds to the immediate postshock temperature at the inner wind shock ($T_s \approx 3m_Hn_H^2v_{\infty}^2/(32k)$ in fully ionized gas). The wind velocity increases with time (see Figure 1), and so the maximum temperature increases with time.

The 1D DEM profiles without conduction are very different to the other results. In this case, the DEM profile consists of discrete values at lower temperatures and a continuous block at higher temperatures. The continuous block corresponds to the postshock temperatures in the accelerating wind. The low temperature discrete values correspond to a numerical effect at the contact discontinuity and will change with numerical resolution. The 1D results with thermal conduction show how heat diffusion spreads out the temperature range of the DEM profile. The 2D results show how mixing due to non-radial flows around the clumps and filaments formed by instabilities fully populates the temperature range. The plateau at $\log T < 5.7$ in the 2D case with conduction corresponds to the conduction layer close to the interface.

Figure 7 shows the DEM distribution of the Wolf-Rayet simulation described earlier. There is a clear separation between the contributions of the fast wind, which dominates the high-temperature range $\log T > 6.5$, and the ambient material, which dominates the range $\log T < 6.5$. Even though the constant fast-wind velocity would suggest a uniform post-shock temperature, the flow of the fast wind around the clumps and filaments leads to a spread of temperatures. By the same token, interacting shock waves in the ablated material around the clumps and filaments raise the temperature in the nebular gas.
Figure 6. Differential emission measure histograms for the planetary nebula $1.5M_\odot$ initial mass numerical simulations. Left: 2D axisymmetric simulation. Right: 1D spherically symmetric simulation. In each case the upper panel shows the results without conduction and the lower panel shows the results for the simulation with thermal conduction.

Figure 7. DEM distribution of the Wolf-Rayet nebula simulation shown in Figure 5. The contribution of the fast wind is shown in red and that of the ambient material is shown in blue.

4.2. Emission Coefficient
The emission coefficient is the combined result of all the atomic processes contributing to the X-ray emission in a desired energy band for gas at a given temperature. The emission coefficient as a function of temperature is defined by

$$
\epsilon(T) = \int_{E_1}^{E_2} \epsilon(T, E) dE
$$

(2)
with $E_1 = 0.3$ keV and $E_2 = 2.0$ keV corresponding to the soft energy band of the XMM-Newton and Chandra telescopes. We used the CHIANTI code [13, 14, 15] to calculate the emission coefficient for chemical abundances appropriate to PN and other astrophysical objects, shown in Figure 8. It is noteworthy that the emission coefficient has a sharp peak at about $\log T = 6.3 \ (T = 2.0 \times 10^6 \text{ K})$.

The emission-weighted average temperature is defined by

$$T_A = \frac{\int T \epsilon(T) \text{DEM}(T) dT}{\int \epsilon(T) \text{DEM}(T) dT}$$

and gives a reasonable estimate to the characteristic temperature derived from X-ray observations. Even though the DEM profiles cover a wide range of temperatures, the sharp peak of the emission coefficient filters out values that are far from the peak value. Figure 9 shows how the average temperature of our simulations changes with time. The simulations with thermal conduction achieve a constant mean temperature, $\log T_A \simeq 6.2$, after only 2000 years. Those without thermal conduction have a slightly higher mean temperature with more variation. The variation can be understood in terms of the DEM profile, which shows a bump close to the maximum temperature at early times that is not seen in the DEM profiles with conduction.

Figure 8. Emission coefficient for ISM, generic galactic planetary nebula and the hydrogen-poor planetary nebula BD+30°3639.

Figure 9. Average temperature of hot gas as a function of post-AGB time for the 1.5$M_\odot$ axisymmetric simulations.

Figure 10. Synthetic spectrum (black line) from the planetary nebula 1.5$M_\odot$ initial mass simulation after 8,000 yrs with principal emission lines indicated. The red line shows the effect of an absorbing neutral column density $N_H = 8 \times 10^{20} \text{ cm}^{-2}$, which is more important at low energies.
Figure 11. Synthetic absorbed, convolved and binned spectra for the 1.5$M_\odot$ model: the error bars correspond to samples with 50 counts (grey) and 200 counts (black). Top row: early time; bottom row: late time. Left-hand panels: without conduction; right-hand panels: with thermal conduction. The absorbing neutral column density is $N_H = 8 \times 10^{20}$ cm$^{-2}$ in all cases.

4.3. X-ray Spectra

The reported X-ray temperatures are derived from X-ray spectra obtained from the Chandra and XMM-Newton telescopes. We can process our numerical simulation results using the DEM profiles and the CHIANTI code to obtain synthetic spectra. Carbon and nitrogen lines are important at low energies, while oxygen and neon lines are important contributors at higher energies. However, the intrinsic spectrum needs to be corrected for interstellar absorption by neutral H along the line of sight, which affects the lowest energy X-rays $E < 0.5$ keV (see Figure 10). The resultant absorbed spectrum then needs to be convolved with the instrumental response matrices and binned to the typical bin resolution of the reported PN observations. The final spectrum has lost much of the detail of the spectral lines (see Figure 11). The changing spectral shape reflects the evolution of the DEM profile and is more marked for models without conduction. The models with thermal conduction show little variation over time, in common with the almost constant mean temperature shown in Figure 9.

These absorbed, convolved, synthetic spectra represent ideal, infinite-exposure-time spectra.
Real observations last a finite amount of time (for PN typically 30,000 seconds) and the photons received in this time register as counts. Several PNe in the CHANPLANS program have fewer than 50 counts due to reduced exposure times. To mimic the observations, we sample the cumulative absorbed spectra a finite number, $N_{\text{counts}}$, times and repeat this operation a large number (10,000) times to obtain good statistics. The error bars shown in Figure 11 represent the standard deviations obtained for $N_{\text{counts}} = 50$ and $N_{\text{counts}} = 200$ sample sizes. We conclude that it is only possible to give a reasonable description of the spectral shape, and hence obtain a reliable X-ray temperature for the gas, with $\geq 200$ counts.

5. Conclusions
Radiation-hydrodynamic simulations reproduce the general properties of Wolf-Rayet and planetary nebulae. 2D simulations allow for the development of instabilities in the swept-up shell of circumstellar material and the formation of clumps and filaments, which promote the turbulent mixing of nebular and fast-wind material. Interactions of non-radial flows result in a full range of plasma temperatures, from the immediate post-shock temperature in the hot wind bubble ($> 10^7$ K) down to the photoionized nebular gas ($\sim 10^4$ K) even when there is no heat diffusion (i.e., thermal conduction).

The emission coefficient integrated over the Chandra and XMM Newton soft X-ray energy bands is sharply peaked at $T \sim 2 \times 10^6$ K, when typical chemical abundances are taken into account. It acts as a filter for the Differential Emission Measure distribution and emphasizes the contribution from gas with temperature close to this peak. This is a natural explanation for the apparent ubiquity of the $T_X \sim 1–3 \times 10^6$ K temperature range derived from observations of the diffuse X-ray emission from planetary nebulae and Wolf-Rayet wind bubbles, without the need to invoke additional physical processes.

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