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# WIND-BLOWN BUBBLES AROUND MASSIVE STARS. THE EFFECTS OF STELLAR WIND AND PHOTO-IONIZATION ON THE CIRCUMSTELLAR MEDIUM

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RESUMEN

Simulamos la evolución del medio circunestelar alrededor de una estrella masiva. Tomamos los parámetros de entrada para nuestra simulación de cálculos de la evolución estelar. Entre ellos, la tasa de pérdida de masa, la velocidad del viento y el número de fotones ionizantes como función del tiempo. Al calcular a lo largo de las diferentes fases evolutivas de estrellas masivas, teniendo en cuenta la historia de su pérdida de masa, hemos simulado la creación y evolución de una burbuja alrededor de la estrella, hasta el momento en que explota como supernova. A diferencia del tratamiento de otros estudios, hemos incluído los efectos causados por la fotoionización. Concluímos de nuestros cálculos que la fotoionización afecta tanto el tamaño como la distribución de masa de burbujas circunestelares durante sus fases de secuencia principal y de supergigante roja.

ABSTRACT

We simulate the evolution of the circumstellar medium around a massive star. We take the relevant input parameters for our simulation from a stellar evolution calculation: mass loss rate, wind velocity and the number of ionizing photons as a function of time. By pursuing the calculation through the various stages of massive star evolution, using a realistic mass loss history as input, we simulate the creation and evolution of a wind-blown bubble around the star up to the time of the supernova explosion. Unlike most previous work on this subject, we include the effects of photo-ionization. From our calculations we can conclude that photo-ionization affects both the size and mass-distribution of the circumstellar bubble during the main sequence and red supergiant stage.

*Key Words:* **H II REGIONS — STARS: CIRCUMSTELLAR MATTER — STARS: MASS LOSS — STARS: WINDS, OUTFLOWS**



## 1. INTRODUCTION

The evolution of the circumstellar medium around a massive star can be divided into three stages, according to the evolution of its central star. A star in the range of 25 $M_\odot$ to 40 $M_\odot$ starts as a main sequence star, develops into a red supergiant and finally, at least for the more massive stars, becomes a Wolf-Rayet star. This means that in the circumstellar medium three interactions take place: First, an interaction between the fast, low density main sequence wind and the interstellar medium; then the slow, high density red supergiant wind hits the bubble created by the main sequence wind. Finally, the massive, high velocity Wolf-Rayet wind sweeps up the remnants of its predecessors. During the main sequence and Wolf-Rayet phases, the star emits a large number of high energy photons. This radiation ionizes the surrounding medium, so rather than expanding into cold gas, the wind encounters an H II region. The interaction between a spherically symmetric wind and the surrounding ambient medium can be approximated by the analytical solution presented by Castor et al. (1975) and Weaver et al. (1977). In this model the interaction between wind and interstellar medium (ISM) works as follows:

The outflowing matter encounters an inner shock, where its velocity is reduced to nearly zero. The kinetic energy of the wind becomes thermal energy. This interaction creates a "hot bubble" of nearly stationary, hot gas. The thermal pressure of the hot bubble drives a shell into the surrounding ISM. Here it is assumed, that the pressure driven shell will be restrained only by the ram pressure created by its own velocity and the density of the surrounding medium.

This assumption is correct if we consider the surrounding medium to be cold. However, if we take photo-ionization into account the situation becomes

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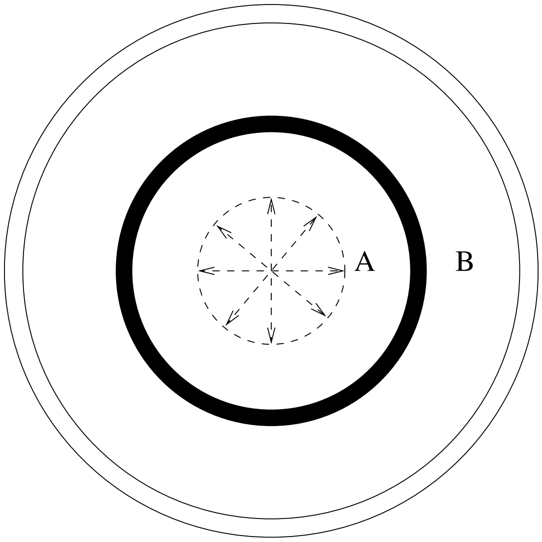


Fig. 1. Schematic view of the circumstellar medium around a massive star. The wind expands freely until it hits the inner shock (dashed line). Here kinetic energy is converted into thermal energy, heating up the "hot bubble" (A), which pushes a shell (thick line) into the H II region (B). The H II region pushes a shell (double line) into the interstellar medium (C).

rather more complicated. First of all, the photo-ionized gas will have a much higher pressure than the cold ISM. Therefore, the H II region will expand, driving a shell into the ISM. Second, the hot-bubble created by the stellar wind will now expand into a hot H II region, which means that the thermal pressure restraining the shell, will no longer be negligeable compared to the ram pressure. A wind-blown bubble expanding into a compact H II region can be observed in NGC 7635. This situation has no analytical solution and must be simulated numerically. A schematic view of the circumstellar medium can be seen in Figure 1.

## 2. MASS LOSS HISTORY OF MASSIVE STARS

We have used the stellar models presented by Schaller et al. (1992). From these models we constructed a mass loss history for a 25 $M_{\odot}$ with solar metallicity. The mass loss history consists of a main sequence phase and a red supergiant (RSG) phase. The mass loss rate and the number of ionizing photons can be taken directly from the model. For the wind velocity during the main sequence we used the escape velocity of the star. The velocity of the RSG wind is more difficult to estimate, since the mechanism that drives the wind is not fully understood. The value we used for the velocity is based on observational data and is the same as in García-Segura et al. (1996); hereafter GLM96.: 15 km/s. The wind parameters used in our calculations can be found in Table 1. Using these values and the analytical solution referred to in §1 we expect the shell to reach a distance of approximately 26 pc from the star. This number is probably too high since some energy is lost to radiative cooling, but earlier results show that this should not make a difference of more than ca. 10 percent.

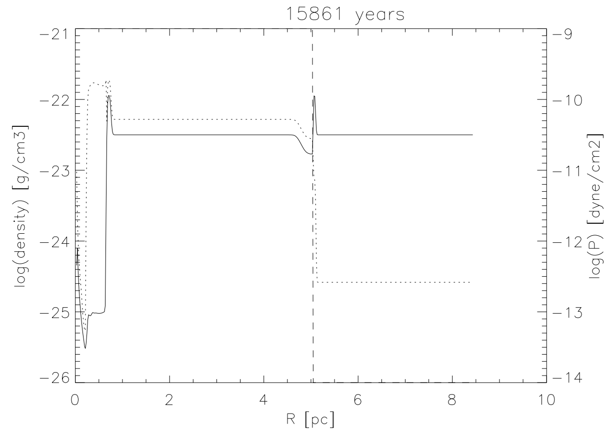


Fig. 2. The density (continuous line) and pressure (dotted line) in the circumstellar medium around a 25 $M_{\odot}$ star during the early main sequence stage, as function of the distance from the central star. The dashed line shows the outer edge of the photo-ionized zone. Both the wind driven shell ($r \simeq 1\,\mathrm{pc}$) and the ionization driven shell ($r \simeq 5\,\mathrm{pc}$) are visible.

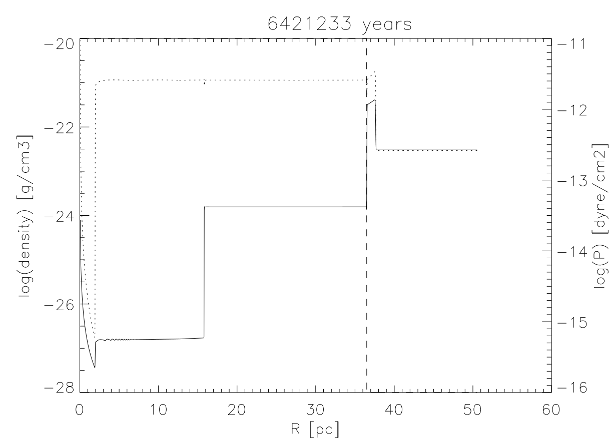


Fig. 3. The same as Figure 2, but at the end of the main sequence stage. Although the inner shell has disappeared, the 'hot-bubble' is still split into two parts: One containing wind material, the other containing ionized ISM.

TABLE 1

MASS LOSS HISTORY FOR A 25 $M_\odot$ STAR

| Stage | Time [yr] | $\dot{M}$ [$M_\odot$ $yr^{-1}$] | v [km $s^{-1}$] | ionizing photon number [$s^{-1}$] |
|---|---|---|---|---|
| main sequence | 6.4215E+06 | 2.1190E-07 | 8.8850E+02 | 1.3740E+48 |
| red supergiant | 7.0591E+06 | 1.2639E-05 | 1.5000E+01 | 1.6293E+37 |

## 3. METHOD

We have simulated the evolution of the circumstellar medium, using a 1D grid with 3000 gridpoints. The calculations were done with the ZEUS-3D code (See Stone & Norman (1992)), which solves the Euler equations on a fixed grid. In order to simulate the wind interactions we have used the method described in GLM96. However, instead of using a time dependent model of the mass loss we assume a two stage model. The values for mass loss rate, wind velocity and photon number as given in Table 1 are averages over the main sequence and red supergiant phases.

Photo-ionization was included in the calculations in the following manner. The stellar evolution model provides us with the total number of photons capable of ionizing hydrogen that the star produces. Using this number as a basis, we move outward through the grid, starting at the inner boundary (closest to the star). At each gridpoint we calculate the number of photons necessary to ionize the matter in the local cell and withdraw that number from the original photon count. As long as we have photons left we can conclude that the matter is ionized, which means that it has a minimum temperature of $10^4$ K. Once the number of available photons is totally spent, we stop and define our location in the grid as the Strömgren Radius. All matter outside this radius is considered neutral, all matter inside as fully ionized. This method has been previously described in García-Segura et al. (1999).

## 4. EVOLUTION OF THE CIRCUMSTELLAR MEDIUM

Figures 2 to 4 illustrate the time evolution of the various structures created in the circumstellar medium. During the main sequence stage, the H II region created by the star is expanding, driving a shell into the interstellar medium ($r \simeq 5$ pc in Fig. 2, and $r \simeq 36$ pc in Fig. 3). At the inner wind shock ($r \simeq 0.2$ pc in Fig. 2), the kinetic energy of the wind is converted into thermal energy, which drives a shell into the H II region ($r \simeq 1$ pc). Figure 3 shows the situation at a later stage. The pressure in the wind bubble and the pressure in the H II region have become equal. As a result, the shell between the two has disappeared, albeit the density discontinuity remains. The outer shell is no longer driven by the photo-ionization, since this driving process stops when pressure equilibrium has been achieved between the H II region and the ISM. This will happen when the H II region has expanded so far that its decrease in density compensates for the higher temperature. The energy needed to drive the outer shell is now provided by the stellar wind.

As the star ages, it becomes a red supergiant with a dense and slow wind. The number of ionizing photons drops. Therefore, the H II region disappears (see Fig. 4). Owing to the low density, recombination will take a long time, but radiative cooling will cause a decrease in thermal pressure. The hot wind-bubble, which keeps its high pressure, expands into the surrounding gas, creating a new shell. A third shell appears close to the star, as the drop in ram

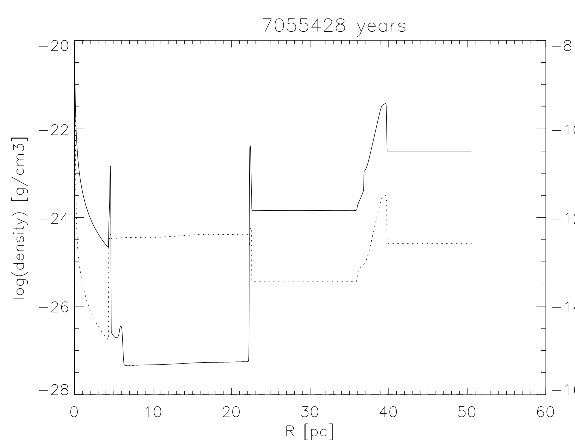


Fig. 4. The same as Figure 3, but at the end of the red supergiant stage. The photo-ionization has disappeared. The outer shell is collapsing inward due to the diminishing pressure. The thermalized main sequence wind drives a new shell into the former H II region, and a third shell is forming where the high density wind reaches the inner shock.

pressure from the RSG wind causes the wind bubble to expand inward, sweeping up the wind material.

## 5. CONCLUSIONS

The influence of photo-ionization on the evolution of the circumstellar medium can be seen both in the size and the mass-distribution of the circumstellar bubble. The total expansion of the circumstellar nebula at the end of the main sequence phase is 35 pc, rather than 26 pc as predicted by the analytical solution mentioned in §1. This changes as the red supergiant stage begins and the number of ionizing photons decreases. The extent of the wind-blown part of the bubble is only 16 pc at the end of the main sequence phase. The presence of an expanding H II region changes the density structure of the nebula during the main sequence. Our main goal at this time is to simulate the circumstellar environment of stars between 25 $M_{\odot}$ and 40 $M_{\odot}$ at the time of the supernova explosion. For those stars that end their lives as Wolf-Rayet stars we intend to provide 2D and 3D simulations of the final phases of the evolution in order to account for the effects of instability in the nebulae around Wolf-Rayet stars.

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*http://www.strw.leidenuniv.nl/AstroHydro3D/*

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