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THE EVOLUTION OF CIRCUMSTELLAR MEDIUM AROUND ROTATING MASSIVE STARS

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RESUMEN

Una estrella rotante de 12 $M_\odot$, después de su evolución de secuencia principal, se convierte en una supergigante roja cuando empieza el quemado de helio en el núcleo. Durante el quemado de helio en el núcleo, y como consecuencia de la variación en la eficacia del quemado de hidrógeno en capa, la estrella pasa por el llamado "lazo azul", i.e., ésta evoluciona hacia una fase de supergigante azul, donde agota el quemado del helio en el núcleo para convertirse de nuevo en una supergigante roja, antes de explotar como supernova. Nosotros intentamos explicar las estructuras en Sher 25 y SN 1987A a través de la asimetría en el viento debida a la rotación. Usamos un modelo de evolución estelar que nos provee de los parámetros del viento dependientes del tiempo, tales como la velocidad del viento y su razón de pérdida de masa. Estos parámetros sirven como entradas para simulaciones hidrodinámicas del medio circunestelar. El lazo azul causa una estructura muy asférica debido a la rotación, mientras que las fases de secuencia principal y supergigante roja son básicamente esféricas. Se concluye que la asimetría de Sher 25 puede ser explicada mediante la rotación estelar.

ABSTRACT

A rotating 12 $M_\odot$ star, after its main-sequence evolution, becomes a redsupergiant when it starts core He burning. During core helium burning, as consequence of a variation of the hydrogen shell burning efficiency, the star undergoes a so called "blue loop", i.e. it evolves into a blue supergiant stage, where it finishes core helium burning and becomes a redsupergiant again, before exploding as a supernova. We try to explain the structures in Sher 25 and in SN 1987A through wind asymmetry caused by rotation. We use a stellar evolution model to provide us with the time dependent stellar wind parameters such as wind velocity and mass-loss rate. These parameters serve as an input for hydrodynamical simulation of the circumstellar medium. The blue loop causes a very aspherical structure due to rotation, while the main sequence and redsupergiant phases are basically spherical. We can conclude that the asymmetry of Sher 25 can be explained through stellar rotation.

Key Words: **HYDRODYNAMICS — ISM: BUBBLES — STARS: SUPERGIANTS — STARS: WINDS, OUTFLOWS**

1. INTRODUCTION

Throughout its life, a 12 $M_\odot$ star emits wind. However, mass loss rate and wind velocity vary with time. While the mass loss rate increases in the post-main sequence phases, the wind velocity scales with the escape velocity from the stellar surface, and is thus large, when the star is hot and compact and small, in the redsupergiant(RSG) stage.

The interaction of a fast wind with a slow preceding wind, but also that of a slow wind with the hot bubble created by a fast preceding wind, give rise to the formation of circumstellar shells.

2. WIND EVOLUTION

A 12 $M_\odot$ star moves in Hertzsprung-Russell diagram from MS stage to RSG only after Hydrogen core burning. The star undergoes a blue-loop and it becomes a blue supergiant (BSG) ending its life as a RSG before it explodes as supernova(SN) like shown in Figure 1.

During their life time stars emit wind. The main sequence wind moves at supersonic velocities and it has a high density. When it collides with the interstellar medium (ISM) it creates a shock. At this moment the wind starts sweeping up matter from the ISM forming a shell which expands outward forming a hot bubble.

The star emits also high energy photons. The photons create a photo-ionized H II region. The

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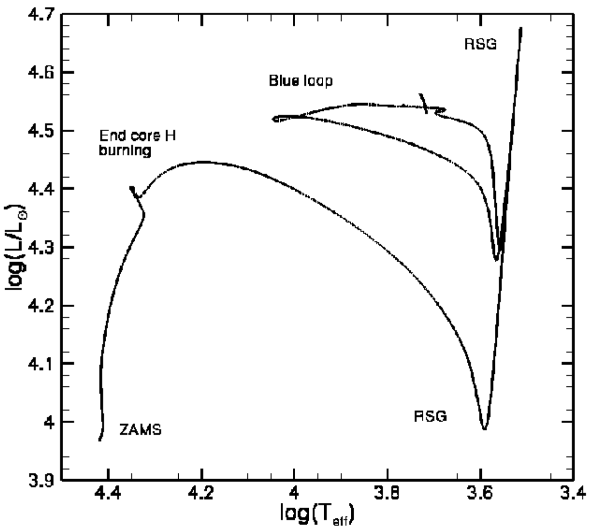

Fig. 1. Evolution of 12 $M_\odot$ in the Hertzprung-Russell diagram.

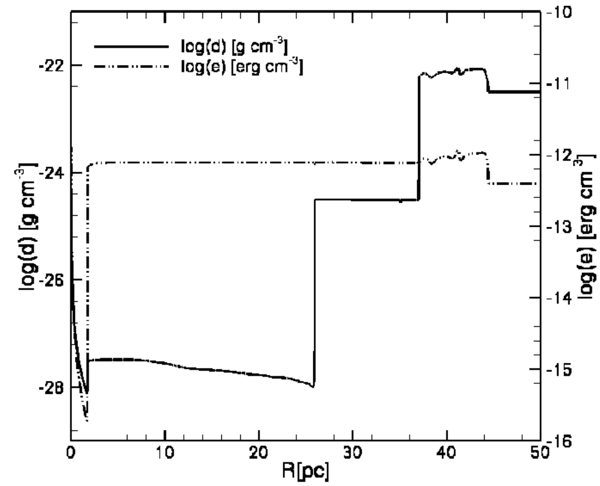

Fig. 2. Structure of circumstellar bubble around 12 $M_\odot$ star in the main sequence phase.This figure shows the density (continuous line) and thermal pressure (dotted line) as a function of radius. From left to right we have the free-streaming main sequence wind; the termination shock at 2 pc; the hot bubble with: the shocked wind material from 2 pc to 26 pc, the H II region from 26 pc to 38 pc; the main sequence shell from 38 pc to 46 pc which moves outwards and the interstellar medium further up to 50 pc.

main sequence wind is expanding now and sweeps up this H II region instead of cold ISM.

In the circumstellar medium four interactions take place: a) first an interaction between the low density, fast main sequence (MS) wind and the interstellar medium; b) second an interaction between the high density, slow red supergiant wind and the hot bubble created by the main sequence wind; c) third an interaction between the fast high density blue supergiant (BSG) wind and the previous RSG wind; violent collision:sweeps up the earlier created structures; d) fourth interaction between the last high density slow RSG wind and the hot bubble created by the MS wind. The high density clumps (results of the collision) will expand in the hot bubble.

3. METHODS

We use the ZEUS3D code by Stone & Norman (1992) to make numerical models of the evolution of the circumstellar medium (CSM). For time saving considerations we use a 1D approximation to model the evolution of main sequence model and the early phase of the first redsupergiant stage. During these stages the wind is almost spherically symmetric due to low rotation rate. In order to obtain an accurate model of the CSM during the blue loop and second redsupergiant phase, we use the output of the 1D simulation as basis for a 2D simulation of the CSM. This method was used by García-Segura et al. (1996a,b) and van Marle et al. (2005).

For 1D simulation we used a grid of 50 pc divided over 4000 grid cells. For the 2D simulation we use a radius versus theta grid of 1000 radial grid points and 200 angular grid points. The angular grid point are evenly spaced over 90 degrees angle with reflective boundary condition at the polar axis and the equator. For fully solving the aspherical winds due to rotation we use a variable resolution for radial grid cells: for the inner part of the bubble from 0.025 pc until 5 pc we have 900 grid points and 100 for the range 5pc and the outer end of the grid.

The stellar evolution was divided into RSG phase followed by BSG and finally RSG before SN explosion.The input was a $12M_\odot$ as calculated by Heger et al. (1998, 2000). The mass-loss rate, wind velocity, number of ionized photons is provided by the model. The effects of photo-ionization are approximated in the simulation by calculating the Strömgren radius along each radial gridline. All matter within Strömgren radius is considered fully ionized, while all matter outside the Strömgren radius is considered neutral using a method described in García-Segura et al. (1999) and van Marle et al. (2005). ISM density is $10^{-22.5}$g cm^{-3}.

4. RESULTS

The shell morphology is as follows: in Figure 2 we see starting from the inner part: the free streaming wind, the wind termination shock, the shocked

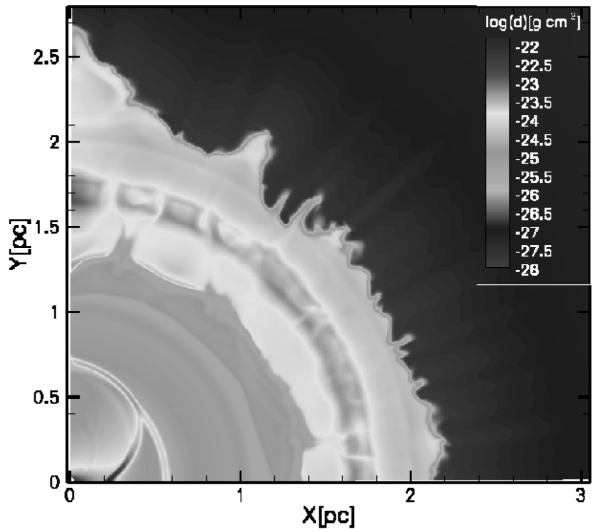

Fig. 3. Logarithm of density [g cm^{-3}] of the circumstellar medium in the bluesupergiant phase at t=2.0038e7 yr, right before the collision with the redsupergiant shell. As can be seen the redsupergiant shell is developing Rayleigh-Taylor instabilities before the collision. The fast BSG wind is sweeping up the preceding RSG wind in a shell, which will collide with the older RSG shell at the wind termination shock (1.4-2 pc). The BSG wind is very a-spherical due to the rapid rotation of the star. Such asymmetry can be observed in Sher 25 and the remnant of supernova 1987 A.

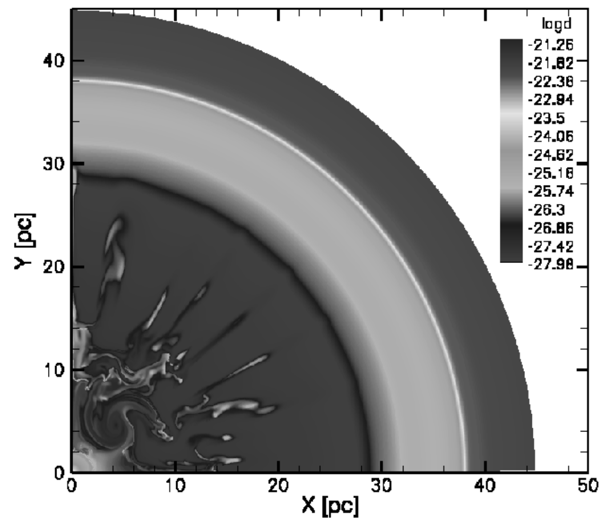

Fig. 4. The logarithm of the density of the circumstellar medium just before the supernova. Moving outward from the central star, we have the free-streaming redsupergiant wind; the redsupergiant shell at the wind termination shock (2 pc); the hot bubble from 2 pc to 30 pc, the new main sequence shell pushed by the hot bubble into the former H II region (since the star no longer emits high energy photons, this region is no longer photo-ionized). The remnant of the old main sequence shell (36-48 pc) an the interstellar medium. The clumps inside the hot bubble are the result of the collision between the BSG wind driven shell and the shell of the preceding RSG phase.

material with the photo-ionized region forming the hot bubble, the MS shell and the ISM.

Moving further into the H-R diagram the star becomes a RSG. The wind coming from a RSG star is very dense but slow comparatively with the MS wind and it heats the hot bubble created previously by the MS shell. The RSG shell is expanding into the hot bubble which converted its entire kinetic energy into thermal energy. The wind coming from RSG because of low temperature at the surface is very poor in high energy photons and for this matter there is no H II region.

After 2.0×10^7 years the star becomes BSG; the wind is very dense and it moves at high velocities: in this respect the BSG wind collides with the RSG wind the results of the collision the high density clumps moving outward into the hot bubble. During this phase, the star rotates rapidly, so the wind is very a-spherical (see Figure 3). We simulate the a-sperical wind by using a simple version of the wind compression model (Bjorkman & Casinelli 1993). The same model as also used by Langer et al. (1999) and García-Segura et al. (1999). An asymmetric structure like this can be observed in Sher 25. A similar structure occors in the supernova remnant of SN 1987A, which seems to indicate that the progenitor star of this supernova exploded during, or shortly after the BSG stage.

The last stage of the 12 $M_\odot$ star is RSG stage where the wind becomes again very slow but with high density and as you can see from Figure 4 following from very close to the star we have: free streaming wind, RSG shell at wind termination shock, the remnants of the collision between BSG shell and old RSG shell, former H II region, old MS shell and ISM. In the RSG stage there is no H II region (no high energy photons). Now the hot bubble pushes a shell into ISM called new MS shell.

The main sequence shell as seen in Figure 4 is driven by thermal pressure of the shocked wind and therefore will be spherical, despite the aspherical wind.

5. CONCLUSION

The evolution of the circumstellar medium around rotating massive stars, in this case a 12 $M_\odot$

star, produces various distinct features, and is determined by the evolution of the central star itself. During the first RSG stage, the wind creates a shell at the location where the RSG windram pressure equals the hot bubble pressure created by the main sequence wind. During the blue loop, the fast BSG wind forms a shell by sweeping up the remaining RGS wind, which then violently collides with the RSG shell (Figure 4), producing knots and filaments which later on get scattered inside the hot bubble. The final RSG stage of the star leads to a RSG shell forming very close to the star, at about 3 pc. This shell will start to interact with the fast supernova ejecta about 100 yr after the explosion. A continuation of the calculations through the stage of SNR formation will allow a comparison with observations of late stages of supernovae and with young SNRs.

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