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OF WOLF-RAYET CENTRAL STARS AND COMMON ENVELOPES

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RESUMEN

Aunque los cálculos de la evolución de estrellas aisladas han logrado recientemente reproducir exitosamente la composición química de las estrellas centrales Wolf-Rayet (WR) deficientes en hidrógeno de las nebulosas planetarias, es claro que las observaciones infrarrojas más recientes implican que se debe adoptar una nueva perspectiva: se encuentra la presencia simultánea del polvo rico en carbono y oxígeno alrededor de la gran mayoría de las estrellas WR centrales frías (un fenómeno poco común para las estrellas centrales ricas en hidrógeno). De Marco & Soker propusieron que la mayoría de las estrellas WR centrales son el resultado de una fusión con una compañera de baja masa durante la fase de la rama asintótica de las gigantes (AGB). En este trabajo, ponemos a prueba parcialmente esta sugerencia especulativa por medio de modelos hidrodinámicos en tres dimensiones, los cuales simulan la fase de envolvente común entre compañeras de masas 0.1 y 0.2 $M_\odot$ y una estrella AGB en el primero y el décimo pulso.

ABSTRACT

Although single star evolutionary calculations have recently succeeded in reproducing the composition of the hydrogen-deficient Wolf-Rayet (WR) central stars of planetary nebulae, it is clear from the latest infrared observations that a new perspective has to be adopted: the simultaneous presence of carbon- and oxygen-rich dust, while being a rare phenomenon for H-rich central stars, is found around the vast majority of cool WR central stars. De Marco & Soker (2002) proposed that the majority of WR central stars are the result of a merger with a low-mass companion during the asymptotic giant branch (AGB) phase. In this work, we partly test this speculative suggestion by 3-dimensional hydrodynamical models, which simulate the common envelope phase between 0.1 and 0.2 $M_\odot$ companions and an AGB star at the first and tenth thermal pulse.

Key Words: **METHODS: NUMERICAL — STARS: AGB AND POST-AGB — STARS: EVOLUTION — STELLAR DYNAMICS**

1. INTRODUCTION

Wolf-Rayet central stars of planetary nebulae (WR CSPN) constitute about 10% of the whole sample of CSPN. They are characterized by extreme hydrogen deficiency and, because of the high opacity of a hydrogen-poor gas mix, they develop strong, dense stellar winds (for a review see Górny & Stasińska 1995). The reason why some CSPN lose all of their hydrogen-rich envelope as well as the hydrogen burning shell is currently explained, in the single star scenario, by the phase in the thermally-pulsating asymptotic giant branch (AGB) when the star leaves the AGB (Herwig 2000).

Infrared Space Observatory results, however, indicate that the single star scenario for the evolution of WR CSPN might not be adequate. The existence of carbon- as well as oxygen-rich dust around the majority of cool WR CSPN is in stark contrast to the fact that known normal CSPN do not show this characteristic (Waters et al. 1998; Cohen et al. 1999).

AGB stars undergo a change between oxygen and carbon chemistry as third dredge-up products are brought to the surface after each thermal pulse. One would then expect to observe both chemistry phases only around AGB central stars that have *just* undergone the transition, because the double dust chemistry visibility is short-lived as both dust shells expand and fade. Seeing the double chemistry in a *post*-AGB star means that the star left the AGB shortly after transitioning between the oxygen and carbon chemistry.

The fact that these objects also show the WR signature led De Marco & Soker (2002, hereafter DS02) to suggest that the same AGB phenomenon promotes the chemistry transition, the departure from the AGB, and the complete loss of the hydrogen-rich layers. They also suggested that the initiator of this chain of events is the penetration of the AGB star envelope by a companion. The mass loss would be due to the deposition of orbital angular momentum, while the chemistry change would be due to additional dredge-up from shear mixing, when the tidally-disrupted companion forms an accretion disk around the core of the AGB star.

Whether all of these events can actually take place is anybody's guess. Despite the lack of a full model of the interaction, DS02 calculated some limiting cases and made some observational predictions.

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A companion that enters the AGB envelope has to reside at a distance of 3 to 10 AU. A shorter distance and the companion would be swallowed by the first giant branch ascent (directly or by tidal capture). A larger distance and not even the radius expansion during the AGB thermal pulses will reach it. The companion mass has to be in the range 0.001 to $0.1\,M_\odot$. A smaller companion will evaporate in the AGB envelope before arriving at the core, a larger one would result in the quick departure of the common envelope and the emergence of a short-period binary. If we presume that all stars between 1 and $10\,M_\odot$ ascend the AGB, and that about 10% of them become WR CSPN, then at least 10% of all stars between 1 and $10\,M_\odot$ must have companions within the appropriate mass and orbital separation ranges.

Although many models exist in the literature which corroborate parts of this scenario (e.g., just to mention a few, Siess & Livio 1999 model planet evaporation in common envelopes, Rosner et al. 2001 model dredge-up by shear mixing—for more references please consult DS02), no known model code exists which can simulate all of the interaction. The closest simulations of the current scenario are those of Sandquist et al. (1998, using the model code of Burkert & Bodenheimer 1993), where AGB stars of 3 and $5\,M_\odot$ are impacted by main sequence companions of 0.4 and $0.6\,M_\odot$, resulting in considerable envelope ejection and stabilization of the binary orbit. With a simple change in parameters, the same technique can be used to test the initial phase of the interaction suggested for the production of WR CSPN, i.e., the interaction between the companion and the envelope of the AGB star.

2. THE MODEL CODE

The code used for our simulations is the one described by Sandquist et al. (1998), to which we refer the reader for further explanations. The model program uses a 3-dimensional hydrodynamic grid technique. Several grids can be nested inside one another to provide higher spatial resolution in the inner regions of the common envelope. Each nested subgrid is centered on the main grid and kept motionless with respect to it. The total mass, energy, and angular momentum of the gas lost from the main grid are followed. The companion as well as the core of the AGB giant are simulated by point masses where the gravitational interaction with the AGB envelope gas is described by a smoothing length formalism.

For our simulations, the main grid has 64^3 cubical zones and measures 9×10^{13} cm on a side, while three nested subgrids have $64\times64\times32$ cubical zones, where the short dimension is perpendicular to the orbital plane. Each subgrid has a resolution twice as high as the grid it is nested in. In the inner grid, the resolution is 1.7×10^{11} cm or $2.4\,R_\odot$. However, due to the chosen smoothing length of 2 and 3 inner cells for the companion and the AGB core, respectively, the maximum resolution that can be realistically simulated is $\sim 12\,R_\odot$. The AGB star structure was computed with the code of Herwig (2000). While on the main sequence, the star had a mass of $1.5\,M_\odot$.

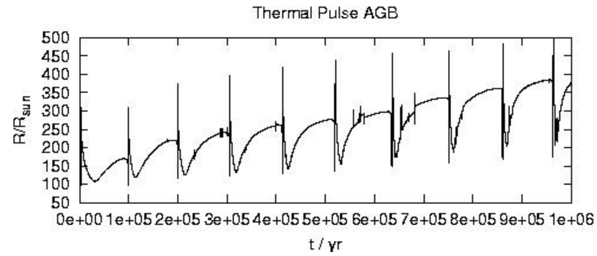

Fig. 1. The radius evolution of an AGB star from the first to the tenth thermal pulse. The star had $1.5\,M_\odot$ while on the main sequence.

3. RESULTS

Four tests were conducted, whose input and output parameters are listed in Table 1. The initial orbital separation was always 2.3 AU and the period 6.2 yr.

In the first test case, labeled "Benchmark" in Table 1, a $0.1\,M_\odot$ companion enters the envelope of a $1.25\,M_\odot$ AGB star when the latter's radius extends to 1.85 AU following its first thermal pulse. After 9 yr the companion has reached a separation of $14\,R_\odot$ and is still spiraling in. By this time only 4% of the envelope has departed (including all unbound gas, whether or not it has left the grid). Unfortunately, the evolution of the system cannot be followed past this point because of low resolution. DS02 calculated that significant tidal disruption of the companion will happen at about $0.1\,R_\odot$ from the center of the AGB. This behavior cannot be confirmed at present.

A second test, called "TP10" in Table 1, was carried out where the AGB star picks up the companion during its tenth thermal pulse. At this stage the star's mass is smaller (1.04 compared to $1.25\,M_\odot$) because of mass loss in the intervening 1 million years (see Figure 1). The AGB star is also more extended, with a 3.0 AU radius. As a result the star's envelope has a lower binding energy. By the $18^{\rm th}$ year of the simulation 84% of the envelope mass has been lost and the orbit has become stable. The simulation has been followed for a total of 6600 days. In the last 1000 days the radius has decreased only 14% compared to the preceeding 1000 days when it decreased

TABLE 1

INPUT AND OUTPUT PARAMETERS FOR THE FOUR COMMON ENVELOPE SIMULATIONS

	"Benchmark"	"TP10"	"Synchronous"	"0.2 $M_\odot$"
Input parameters				
AGB Core Mass ($M_\odot$)	0.56	0.60	0.56	0.56
AGB Envelope Mass ($M_\odot$)	0.69	0.44	0.69	0.69
AGB Envelope Radius (AU)	1.85	3.00	1.85	1.85
Companion Mass ($M_\odot$)	0.1	0.1	0.1	0.2
Output parameters				
Envelope Mass Lost (%)	4	84	25	57
Final core-companion separation (AU)	0.09	0.41	0.06	0.10
Timescale (yr)	9	18	10	9
Fate	Collides?	Stops?	Stops	Stops

by 25%. By the end of our simulation the companion is at 86 $R_\odot$ from the AGB core. It is likely that in this simulation no core-core collision will happen and a short period binary will emerge. In such a case no WR CSPN would result, as no core-core collision extra mixing is expected.

In the third test case, called "Synchronous" in Table 1, the AGB star's envelope was set in synchronous rotation with the companion at the start of the simulation, i.e., at a speed of 11 km s^{-1}, reasonable for an AGB star. The envelope rotation promotes much more mass loss than when the envelope is not rotating: 25% of the envelope is lost in 10 years. The core-companion separation at the end of the simulation is $\sim 10\,R_\odot$, and is diminishing quite slowly (by only 7% in the last 400 days of the simulation, compared to 18% in the preceeding 400 days). It is likely that the orbit of the companion would stabilize before it collides with the AGB core.

In the last test, termed "0.2 $M_\odot$" in Table 1, the companion's mass was 0.2 $M_\odot$. The increased mass of the companion decisively determines a much increased mass loss. 57% of the entire envelope is lost in 9 years and a separation of 15 $R_\odot$ is reached. Once again, it is likely that the companion's orbit will become stable.

In all four cases, the star shape is altered from spherical symmetry. In Figure 2 we show density contour plots of the equatorial and perpendicular planes taken at 4 different times during the Benchmark simulation (rows 1 and 2 in the figure), as well as vertical cuts for the TP10 simulation (row 3). In the Benchmark case the star deformation at the end of the simulation is not extreme. If the companion's collision with the core does not result in a major disruption of the AGB star, it is likely that the star would recover its equilibrium shape in a short time. If so, then any further mass loss would recover the symmetry it had before the common envelope phase. On the other hand, it is likely that when the 0.1 $M_\odot$ companion reaches the burning shell at the core-envelope boundary of the AGB star, whether it is still whole or tidally broken up, something will happen. The geometry of the short and intense burst of mass loss in the latter three test cases is highly bipolar as can be seen from the vertical cut contour plot of the TP10 simulation at 18 years from the beginning (last panel, row 3 in Fig. 2). It is tempting to suggest that such a short, intense burst of mass loss, if it happens, should produce PN with distinctive characteristics. Further details of these simulations, will be exposed in De Marco et al. (2003).

Returning to the evolution of WR CSPN, the current tests confirm the back-of-the-envelope calculation of DS02 that the upper mass limit for core-core collision is 0.1 $M_\odot$ (although envelope rotation or a later envelope penetration time might mean that even a 0.1 $M_\odot$ companion will not collide with the core). A larger companion promotes sufficient mass loss for its orbit to stabilize and for the system to emerge as a short period binary. The idea of DS02 that a companion will promote sufficient mass loss for departure of the primary from the AGB *and* will then go on to collide with the core, might therefore not be entirely correct. However, since it is unknown what happens when the companion collides with the burning shell at the AGB core boundary, this scenario remains untested.

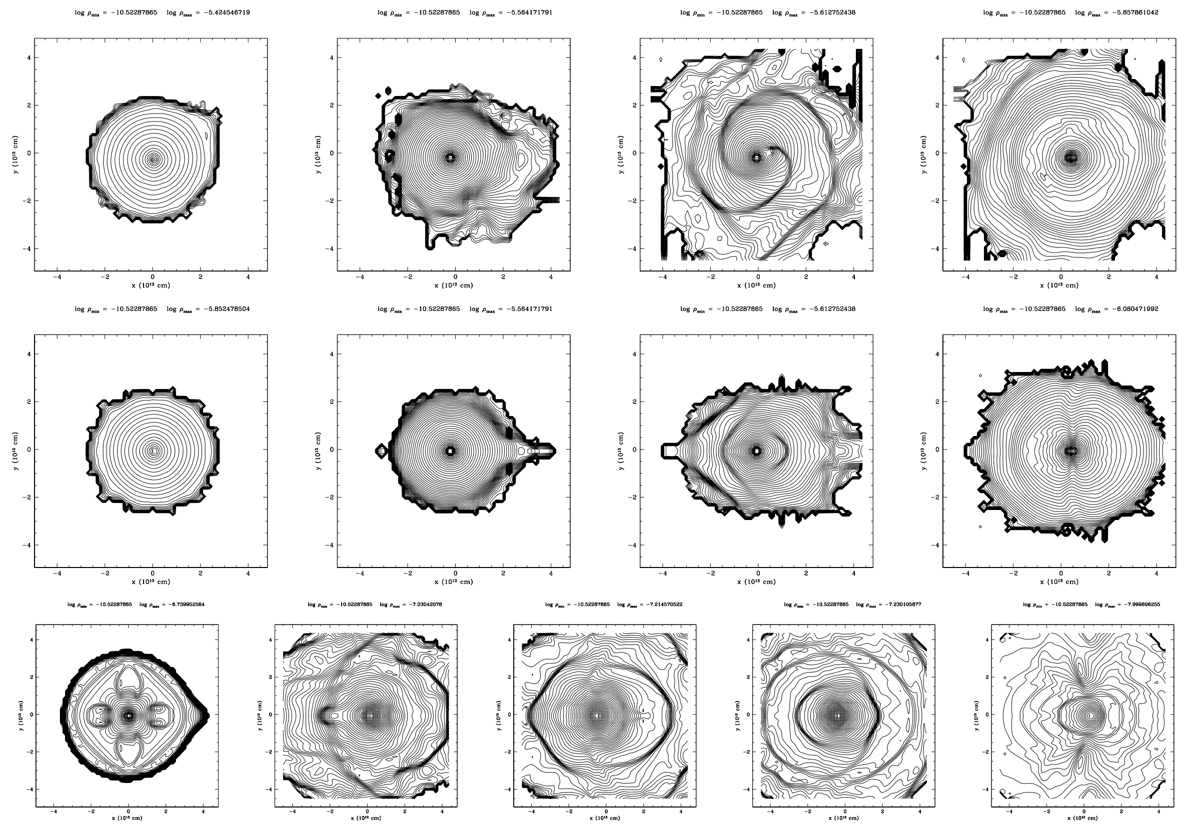

Fig. 2. Density contours for 2-D cuts on the orbital (first row) and perpendicular (second row) planes for the Benchmark simulation. Thirty contour lines are used in log-space between $\log(\rho/\mathrm{gr\,cm^{-3}}) = -10.5$ (outskirts) and -5.5 (core). A comparison with the vertical cuts of the TP10 simulation (third row) is also carried out. The first four columns correspond to snapshots in time taken 0.5, 3, 6 and 9 years after the beginning of the simulation. For the TP10 test (third row) the fifth column corresponds to 18 years.

On the other hand simulations, such as the ones carried out at present, can put fundamental constraints on the common envelope ejection efficiency and can provide a theoretical explanation for the frequency of short period binaries, whether they later become novae and dwarf novae, or CSPN.

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