RevMexAA (Serie de Conferencias), **18**, 24–30 (2003)

WOLF-RAYET CENTRAL STARS AND THE BINARY EVOLUTION CHANNEL

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RESUMEN

Cálculos recientes de la evolución de estrellas sencillas han tenido éxito en reproducir la composición de estrellas Wolf-Rayet (WR) deficientes en hidrógeno que son además estrellas centrales de nebulosas planetarias. Sin embargo, las observaciones infrarrojas más recientes dejan claro que el esquema de estrellas sencillas no concuerda con las propiedades del polvo que rodea a muchas estrellas centrales tipo WR. Por otro lado, la binariedad podria explicar las observaciones en el infrarrojo así como ofrecer una posibilidad de remover la envoltura rica en H de la estrella. En este trabajo proponemos dos esquemas con estrellas binarias originalmente propuestos por De Marco & Soker en relación a las estrellas centrales tipo WR. En el primero, un sistema binario cercano da como resultado el regreso de material eyectado a la estrella y eventualmente una estrella central deficiente en H. Este esquema se invoca para explicar la estrella central CPD–56°8032 en [WC10] y su disco de polvo. El segundo esquema propone que la mayoría de las estrellas centrales tipo WR son resultado de una fusión con una compañera de baja masa durante la fase AGB. Modelamos este esquema por medio de simulaciones hidrodinámicas en 3D, que simulan la fase de envolvente común entre una estrella AGB y una compañera de entre 0.1 and 0.2-$M_\odot$ durante el primer y décimo pulso térmico.

ABSTRACT

Single star evolutionary calculations have recently succeeded in reproducing the composition of the hydrogen-deficient Wolf-Rayet (WR) central stars of planetary nebula (PN). However, the latest infra-red observations, made it clear that the single star scenario is at odds with the properties of the dust surrounding many WR central stars. Binarity, on the other hand, can potentially explain the infra-red observations, as well as offer a viable way of depleting a star of its outer, H-rich envelope. In this work we expose two binary scenarios first discussed in connection to WR central stars by De Marco & Soker. In the first, a close binary system results in back-flowing material and ultimately in a H-deficient central star of PN. This scenario, is invoked to explain the [WC10] central star CPD–56°8032 and its dusty disk. The second scenario envisages 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. This scenario is partly tested here, 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**

1. INTRODUCTION

Wolf-Rayet central stars of planetary nebula (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 H-poor gas mix, they develop strong, dense stellar winds (for a review see Gorny & Stasinska 1995). The reason why some CSPN lose all of their H-rich envelope as well as the H-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).

Infra-red Space Observatory (ISO) results, however, indicate that the single star scenario for the evolution of WR CSPN might not be fully adequate. The existence of a carbon- as well as oxygen-rich dust around the majority of cool WR CSPN ([WCL][5]) is in stark contrast to the fact that known normal CSPN do not exhibit this characteristic (Waters et al. [1998]; Cohen et al. [1999]).

The dual dust chemistry phenomenon in PNe ap-

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[5]The [] distinguishes the WR CSPN class from the massive WR stars. The "C" spells out the the WR CSPN are WR stars of the carbon sequence, rather than of the nitrogen (WN) sequence. The [WCL] and [WCE] classes simply differentiate between "late" (cooler stars) and "early" (hotter stars, probably descending from the cooler ones).

The eighth Mexico-Texas Conference on Astrophysics: Energetics of Cosmic Plasmas (Mexico City, Mexico, 31 October - November 2, 2002)
Editors: Mauricio Reyes-Ruiz & Enrique Vazquez-Semadeni

pears to show a strong correlation with the presence of [WCL] CSPN - seven out of ten [WC8-11] nuclei studied by Cohen et al. (2002) and other authors (for a collection see De Marco & Soker [2002], hereafter DS02) showed similar dual dust chemistries. In the context of a single star scenario, the dual dust chemistry of [WCL] CSPN would imply a recent transition (within the last ~1000 yr) between O- and the C-rich surface chemistries (e.g. Waters et al. 1998). However, the probability of finding a post-AGB object that had recently changed from an O-rich to a C-rich surface chemistry due to a third dredge-up event should be fairly low, difficult to reconcile with the existence of seven such objects.

An alternative scenario envisages these systems as binaries (Cohen et al. 1999, 2002, DS02), in which the O-rich silicates are trapped in a disk as a result of a past mass transfer event, with the C-rich particles being more widely distributed in the nebula as a result of later ejections of C-rich material in non-equatorial directions.

A third scenario, proposed by DS02 sees the WR CSPN progenitor progress through a fast change between O- and C-rich chemistry, initiated by a low-mass companion penetrating the AGB envelope. This scenario, has the appeal that the chemistry change as well as the departure from the AGB and the hydrogen deficiency would be related to the same physical phenomenon. On the other hand, the complex series of events which this scenario invokes, cannot be guaranteed to happen in the correct sequence without a comprehensive model.

In this paper, we describe the various scenarios and the observations that prompted their invention. We also show how parts of these scenarios can be tested using currently available model codes.

2. THE [WC10] CPD-56^{O}8032 AND ITS DUSTY DISK

The cool [WC10] WR CSPN CPD–56°8032 and its surrounding PN are exceptional in many ways. Cohen et al. (1986) found its mid-infrared KAO spectrum to show very strong unidentified infrared bands (UIBs – attributed to polycyclic aromatic hydrocarbons, PAHs). Indeed, its nebular C/O ratio (C/O=12 by number; De Marco, Barlow & Storey 1997) are amongst the largest known. It was therefore a major surprise when mid- and far-IR ISO spectra showed the presence of many emission features longwards of 20 μm that could be attributed to crystalline silicate (Cohen et al. 1999), indicating the simultaneous presence of both C-rich dust and O-rich dust. Another intriguing aspect of CPD–56°8032 is that the star can undergo brightness changes of $\Delta m_{vis} \sim 1.5$ mag with a five-year quasi-period (Cohen et al. 2000), the most recent minimum having occurred in May 2001 (Fig. 1).

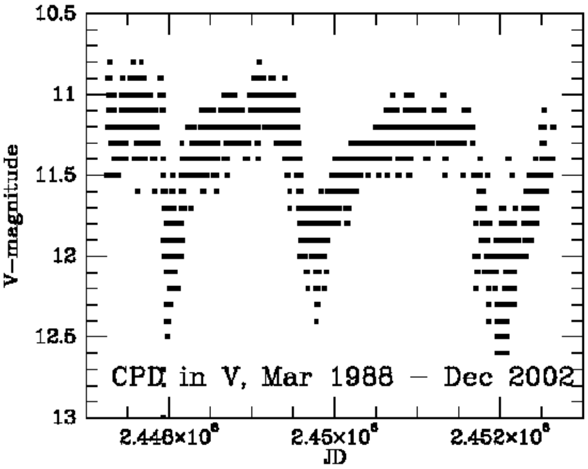

Fig. 1. The visual light-curve of CPD-56°8032, extending the work of Jones et al. (1999) to the end of 2002. The May 2001 STIS spectra were taken at the bottom of the most recent light-curve minimum.

HST/STIS near-UV and optical long-slit spectroscopy of CPD–56°8032 and two other dual dust chemistry [WCL] PNe (programme GO-8711), was carried out in order to measure the nebular C/O ratio as a function of nebular radius, with the aim of searching for a gradient or discontinuity in the C/O ratio that could indicate the locations of the C-rich and O-rich dust components. The STIS spectra of CPD–56°8032 were obtained in May 2001, very close to the minimum of its most recent deep light decline. It came as a surprise to find that the STIS/MAMA UV long-slit spectrum of the central star was split into two components, separated by 0.10 arcsec (four MAMA pixels), corresponding to a separation of 135 AU at 1.35 kpc (see Fig. 2, top). A spectrum of a very similar [WC10] star+nebula, He 2-113, taken with the same instrument at about the same time, did not exhibit this peculiarity (Fig. 2, bottom), confirming that instrumental problems were not responsible for the splitting of CPD–56°8032 's UV spectrum. A cross-cut through the STIS/CCD spectrum of CPD–56°8032 at 3700 Å was significantly broader than a similar cut through He 2-113's central star at the same wavelength, while cross-cuts through CPD–56°8032 at 7200 Å and 8900 Å showed no broadening relative to He 2-113 (see Fig. 3 of De Marco et al. 2002)

The two components of CPD–56°8032's split UV spectrum are similar (Fig. 2), both displaying the same Wolf-Rayet emission lines. The only difference

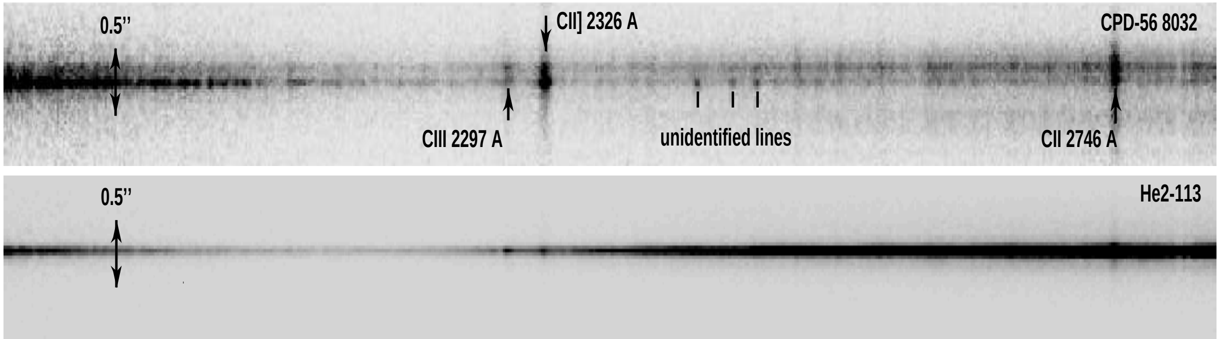

Fig. 2. STIS/MAMA 2-D spectra of the planetary nebulae He 3-1333 (top; central star = CPD–56°8032 = V837 Ara) and He 2-113 (bottom; central star = Hen 1044).

between them is in their continuum shapes, indicating differing reddening/scattering contributions. On the basis of the Cycle 9 STIS observations, De Marco et al. (2002) reached the conclusion that the light observed during decline must be reflected by a thick dust torus observed nearly edge-on, which obscures direct light from CPD–56°8032 and whose upper and lower limbs reflect light from the star towards the observer. The light variability could be due to a dust clump within the disk, precession of the disk orbital plane, or, possibly, the binary motion of the star which brings it in and out of alignment with the disk. The latter scenario is similar to one that has been proposed for the Red Rectangle (HD 44179; e.g. Waelkens et al. 1996, Men'shchikov et al. 2002), a dual-dust chemistry proto-PN.

A refinement of the latter scenario is the one that offers the best chance of explaining the observations. If CPD–56°8032's minimum light spectrum were truly the result of reflected light only, while the maximum light spectrum were a combination of reflected and direct star light, one would expect the maximum light spectrum to be much brighter than the minimum light spectrum. This is because reflection is not very efficient, a few percent at most (Whitney & Hartmann 1992), and the difference between reflected light only, and reflected *plus* transmitted light would be large. However, the brightness difference between CPD–56°8032's minimum and maximum light is only a mere m_{vis}~1.6 mag (Fig. 1). We therefore propose that *both* at minimum and maximum light CPD–56°8032's light is seen in reflection only. This can be achieved if the entire binary orbit is within the obscuring disk. CPD–56°8032's companion, which could be a low mass main sequence star, could be orbiting CPD–56°8032 accompanied by a trail of debris (this has been observed, for instance in the young solar-like star KH15D; Herbst et al. 2002). CPD–56°8032's light, as seen by the disk's rims would be periodically eclipsed by the companion plus debris, so that the fraction of light that is reflected back to Earth would also be periodically varying. A debris trail would help explain the shape of lightcurve (sharp declines ans gentle rises).

The binary hypothesis for CPD–56°8032, also fits in with the bipolar nature of CPD–56°8032's PN. On pre-COSTAR HST/WFPC pictures taken in Hβ as well as in our Cycle 9 HST/STIS peakup images, CPD–56°8032's PN reveals a strongly bipolar nature (De Marco et al. 1997,2002). According to DS02, CPD–56°8032's morphology could be consistent with a close binary companion which did not undergo a common envelope with the primary. The disk would be created by AGB wind material back-flowing onto the star. The H-deficient nature of CPD–56°8032 would be brought about either by a thermal pulse (like in the single star scenario of Herwig et al. 1999) or by extra mixing and enhanced mass-loss induced by the accretion disk.

CPD–56°8032 could therefore be a WR CSPN in virtue of mass-loss induced by the companion. The companion would be orbiting within the outer reaches of the WR wind (at about 600 $R_\odot$ which is beyond the nominal outer limit of the wind of ~200 $R_\odot$ [De Marco & Crowther 1998], but still in a region of relatively high density) where it triggers dust condensation which trails it in a dust wake (in a similar fashon to the dust trail seen orbiting with the O star in the WR+O massive star binary WR104; Tuthill et al. [1999]). The outer, larger, optically thick dust torus would be left over from the system's AGB evolution.

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3. THE COMMON ENVELOPE SCENARIO FOR [WR] CENTRAL STARS

A common envelope interaction during the AGB was invoked by DS02 to explain the majority of WR CSPN, in particular those residing within elliptical and extreme elliptical PNe. The appeal of the common envelope scenario is that the penetration of the companion into the envelope of the AGB star *triggers* the double dust chemistry, the departure from the AGB and the hydrogen deficiency. This would be a clean way to explain the exclusive association of double-dust chemistry with the WR character of the central star. After the penetration of the AGB envelope by the 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. A companion that enters the AGB envelope has to reside at a distance of 3-10 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 0.001–0.1 $M_\odot$. 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. Additionally, 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.

3.1. *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 $64\times64\times64$ 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 $M_\odot$.

3.2. *Some Model 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 3). The AGB star is also more extended, with a 3.00 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 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 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 beginning 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 (only by 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 the companion 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 4 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 Figure 4), as well as vertical cuts for the TP10 simulation (row 3 in Figure 4). 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

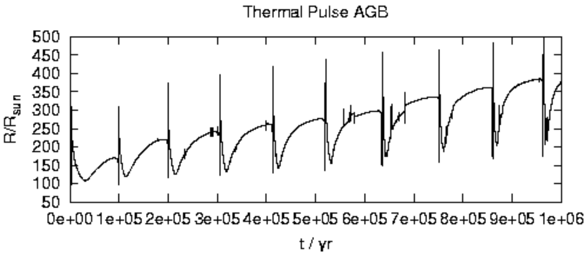

Fig. 3. The radius evolution of an AGB star from the first to the tenth thermal pulse. The star had 1.5 $M_\odot$ while on the main sequence.

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 Figure 4). 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. (in preparation).

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.

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.

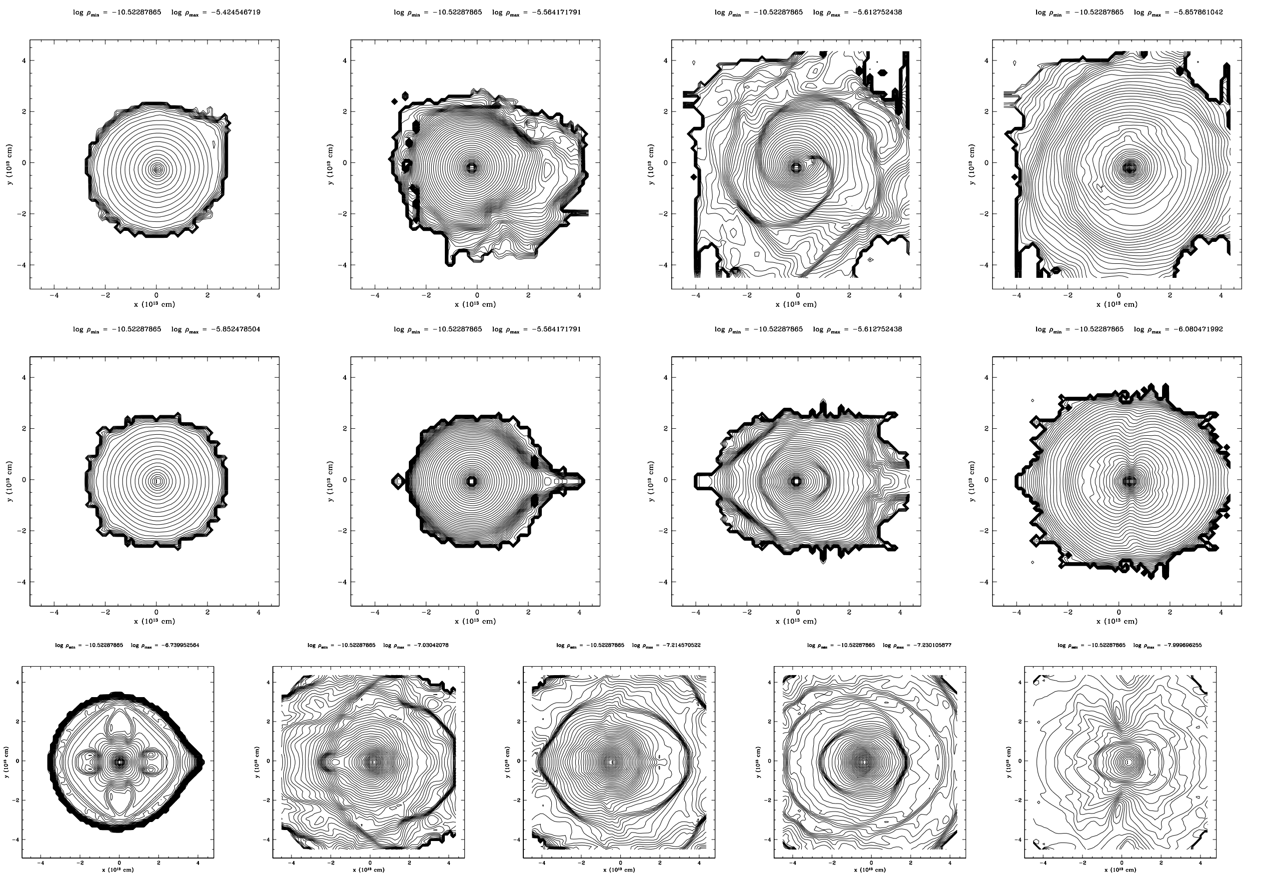

Fig. 4. Density contours (30 contour lines are used in log-space between $\log(\rho\ [\mathrm{gr\ cm^{-3}}])=-10.5$[outskirts] and -5.5[core]) for 2-D cuts on the orbital (first row) and perpendicular (second row) planes for the Benchmark simulation. A comparison with the vertical cuts of the TP10 simulation (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.

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

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4. CONCLUSIONS

Before ISO, the only characteristic distinguishing the WR CSPN from H-rich CSPN was the star. No other observed characteristic could tell the two groups apart. The double-dust circumstellar chemistry was the first non-stellar characteristic to further distinguish the two groups. It is likely that as WR CSPN receive more attention (binarity and common envelopes are important evolutionary channels), a new generation of observations will reveal more and more differences between the WR and the H-rich central stars and their PN. If these new observations continue to support a binary channel for the WR CSPN, this class will become closely related with an important issue in stellar evolution, i.e. binarity and what that might do to evolved stars. If the common envelope scenario also remains associated with WR CSPN, we would have an even more important association of this class with stellar evolution, namely the possibility of understanding the role of planets, brown dwarfs and low-mass main sequence stars in the lives of giants. The next few years of observations and models will no doubt settle the issue of whether the WR CSPN class is just another weird and insignificant stellar class, or the tell-tale signature of an important mechanism on the AGB.

OD is grateful to Janet Jeppson Asimov for financial support. ELS is partly supported by NSF grant AST-0098696. M-MML acknowledges NSF CAREER grant AST99-85392. RET acknowledges support from NSF grants AST-9727875 and AST-0200876. FH thanks D.A. VandenBerg. Albert Jones is acknowledged for the CPD–56°8032 lightcurve and his continuing efforts in observing variable stars in the southern skies.

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