SESSION 6

LOW MASS WOLF-RAYET STARS - RING NEBULAE

Chairman: K. GARMANY

Introductory speakers: A. RENZINI
S. HEAP

1. A.J. WILLIS and D.J. STICKLAND: The peculiar binary system HD 45166 (SdO+B8V?).

2. P. BENVENUTI, M. PERINOTTO and A.J. WILLIS: The UV spectrum of the central star of NGC 40.

3. R.H. MENDEZ and V.S. NIEMELA: A reclassification of WC and "O VI" central stars of planetary nebulae and comparison with population I WC stars.

4. J.N. HECKATHORN, F.C. BRUHWEILER and T.R. GULL: A new search for nebulae surrounding Wolf-Rayet stars.

5. Y.-H. CHU: Ring nebulae associated with Wolf-Rayet stars.

6. M.C. LORTET, G. TESTOR and V.S. NIEMELA: Ring nebulae around WC6 stars: NGC 6357 around HD 157504.

7. M. ROSADO, G. MONNET, A. LAVAL and Y. GEORGELIN: Kinematics of the ring-shaped nebula N 206 in the LMC.

8. A. TUTUKOV: WR stars with ring nebulae.

9. D. STICKLAND and A.J. WILLIS: IUE observations of the WN-c star HD 62910.

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LOW MASS WOLF-RAYET STARS: THEORY

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1. INTRODUCTION

It is well known that the Wolf-Rayet phenomenon is not restricted to some bright and massive stars, presumably in their core hydrogen-burning or helium-burning phase, but that it is also encountered among the central stars of some planetary nebulae (PNe). The PN nuclei are generally regarded as the evolutionary product of low and intermediate mass stars (with initial masses M_i below $\sim 5\ M_\odot$), which have lost most of their hydrogen-rich envelope during the so-called Asymptotic Giant Branch (AGB) phase. Correspondingly, their present mass cannot exceed the Chandrasekhar limit ($\sim 1.4\ M_\odot$), and their internal structure consists of a highly degenerate carbon-oxygen core containing most of the stellar mass, surrounded by an *intershell* region of mass ΔM_{CSH}, and by a very low-mass envelope ($M_e < \sim 10^{-3}\ M_\odot$).

The fact that similar spectra are exhibited by stars of so different mass, internal structure, and evolutionary phase, can be interpreted as a strong indication that the WR effect is indeed an *atmospheric* phenomenon, always arising once howsoever some particular combination of the atmospheric parameters (temperature, gravity and composition) is produced.

In the frame of the current standard evolutionary models, the intershell mass ΔM_{CSH} is a function of the core mass M_H, defined as the mass inside the hydrogen-helium discontinuity. Thus, ΔM_{CSH} decreases from $\sim 0.02\ M_\odot$ to $\sim 2\ 10^{-5}\ M_\odot$, for M_H increasing from 0.5 to 1.4 $M_\odot$ (cf. Iben and Truran 1978). The composition of the intershell region depends moderately on M_H, helium and carbon are the dominant species, and the carbon abundance by mass is typically around 25 % (cf. Renzini and Voli 1981).

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The composition of the residual hydrogen-rich envelope results from the combined effect of the various dredge-up events having mixed to the surface nuclearly processed materials during the whole previous stellar history. Following Iben and Truran (1978), one distinguishes three dredge-up phases: the first dredge-up occurs when the evolving star reaches the red giant branch for the first time, the second dredge-up (which does not operate in stars less massive than a critical value) takes place when stars reach the AGB following the helium exhaustion in the core, and, finally, the third dredge-up consists in a number of mixing episodes, each of them triggered by the various helium-shell flashes occurring during the AGB phase. The cumulative effect of all these mixing events has been calculated by Iben and Truran (1978), Becker and Iben (1980), and Renzini and Voli (1981), who have also included the effect of the CNO processing which can operate at the base of the convective envelope of AGB stars. The result is that the abundance ratios He/H, C/O and N/O are significantly affected, but extreme hydrogen deficient stars ($0.0 \leq n_H \ll n_{He}$) are never produced in this framework. Conversely, how such stars could be generated is the main concern of this paper.

All PN nuclei exhibiting a WR spectrum belong to the WC variety, with a minority of them also showing some WN characteristics, and, correspondingly, being classified as WCN stars (Heap, this volume). From what we heard till now at this meeting, there seems to be an almost generalized agreement according to which: i) WC stars are virtually hydrogen free, and ii) the nitrogen abundance in WC and WCN stars is very uncertain (because of the lack of detailed atmosphere-wind models), but is possibly very low. On the basis of these evidences it seems quite legitimate to suspect that WC (and possibly WCN) PN nuclei are stars exposing their intershell region (Renzini 1979, 1981b), i.e. post-AGB stars which in one way or another have totally lost (or destroyed) their residual hydrogen-rich envelope. Before discussing how this could happen, it is worth recalling some relevant characteristics of the helium-shell flashes and of the post-AGB evolution.

2. SOME CHARACTERISTICS OF THE HELIUM SHELL FLASHES AND OF THE POST-AGB EVOLUTION

The detailed properties of the helium-shell flashes, also called thermal pulses, occurring during the AGB phase have been described in a number of papers (e.g. Iben 1976, 1977, 1981; Sweigart 1976; Sackmann 1980a; Becker 1981; Iben and Renzini 1982), and here just a few relevant features of the pulses are briefly discussed.

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The interpulse time Δt_{ip}, i.e. the time between two successive pulses, is a monotonically decreasing function of M_H, with Δt_{ip} ranging from $\sim$300,000 yr for $M_H = 0.5$, down to $\sim$30 yr for $M_H = 1.4$.

The surface luminosity L_s during most of the interpulse period is related to M_H by the expression (Iben and Truran 1978):

$$L_s = \sim 6.34\ 10^4 (M_H - 0.44)(M/7)^{0.19} \quad (1)$$

where M is the stellar mass and all quantities are in solar units. However, for low core masses ($M_H < \sim 0.6$), Eq. (1) somewhat overestimates L_s (for more details see Iben and Renzini 1982).

At pulse peak the rate of the triple-α energy release $-L_{He}-$ reaches 10^7-10^8 $L_\odot$ (cf. Becker 1981), causing most of the intershell region to become convective for a while. As discussed in many papers, in AGB stars an entropy barrier prevents the intershell convection from reaching into the hydrogen-rich envelope (cf. Iben 1977, and references therein). Following the disappearance of the intershell convection L_{He} steadly decreases from $L_{He} \simeq L_s$ to $\sim$100 $L_\odot$, in a time roughly equal to $\frac{1}{2}\Delta t_{ip}$. The time required for L_{He} to decrease from $\sim L_s$ to 1000 $L_\odot$ (t_b) is about 1/5 the interpulse time (i.e. $t_b \simeq 0.2\Delta t_{ip}$).

As L_{He} decreases, the hydrogen-burning shell progressively reactivates, and, when it has traversed a mass ΔM_H, a new flash is initiated in the intershell region. Clearly, ΔM_H is the increase in core mass during one cycle, and it ranges from $\sim 2.6\ 10^{-3}$ $M_\odot$ for $M_H = 0.5$, down to $\sim 1.7\ 10^{-5}$ for $M_H = 1.4$.

The total number of pulses experienced during the AGB phase is extremely sensitive to the stellar initial mass M_i. Less massive stars ($M_i \simeq M_\odot$) suffer just a dozen pulses, while more massive stars ($M_i > \sim 5$) in which the core approaches the Chandrasekhar limit experience $\sim$9000 thermal pulses (cf. Renzini and Voli 1981).

According to the current picture for the AGB evolution, stars ascend the AGB losing mass (wind regime) until the envelope mass M_e drops below a critical value M_{PN} (function of M_H). When this happens the envelope is rapidly ejected (superwind regime) and the AGB phase is terminated (Wood and Cahn 1977; Iben and Truran 1978; Renzini and Voli 1981; Renzini 1981a,b; Iben and Renzini 1982). During the superwind regime M_e is rapidly decreasing, and when another critical value of the envelope mass is reached (M_{eD}) the star begins to depart from the AGB, moving to higher and higher temperatures. M_{eD} is of the order of 0.001-0.01 $M_\odot$, and depends rather moderately on M_H (see Iben and Renzini 1982, and references therein). It is argued that the rapid decrease in stellar radius will ultimately quench the superwind instability, this happening when M_e falls below a third critical value M_{eR}. It is worth warning that this picture is essentially qualitative, as it is presently impossible to obtain M_{PN} and M_{eR} from first principles. Obviously, both these quantities are expected to be functions of M_H (and probably of composition as well).

The subsequent post-AGB evolution proceeds at nearly constant luminosity (still given by Eq.(1)), until most of the residual envelope is processed through the hydrogen-burning shell. The maximum temperature reached during this blueward evolution ranges from $\sim 10^5$ K (for $M_H = 0.5$) up to $\sim 10^6$ K (for $M_H = 1.4$), then stars fade and cool approaching the corresponding white dwarf cooling sequences (Paczynski 1971). All relevant timescales during the post-AGB phase are extremely sensitive to M_H.

In conclusion, the temperatures and luminosities of model post-AGB stars encompass the corresponding values observationally derived for PN nuclei in general, and for those central stars showing a WR spectrum in particular. Although a detailed quantitative understanding of PN nuclei presents several fascinating complications (cf. Renzini 1979, 1981a,b; Schönberner and Weidemann 1981; Schönberner 1981; Iben and Renzini 1982), we now focus on just one aspect of the problem, i.e. on how some post-AGB stars could eventually expose their intershell region, an event which, we speculate, could turn a PN nucleus into a WR star.

3. POSSIBLE EFFECTS OF THE LAST HELIUM SHELL FLASH

Before becoming white dwarfs the stars terminating in this way their evolutionary history will suffer a last helium shell flash. This final pulse can take place while the star is anywhere between its AGB phase and its final approach to the WD cooling sequence. We distinguish three main cases, althogh less frequent possibilities could be envisaged. In *Case 1* the last pulse occurs *before* the onset of the superwind regime, when the star is still on the AGB. In *Case 2* the last pulse takes place just *after* the termination of the superwind regime, when the envelope mass is < $\sim M_{eR}$ and the star is still close to the AGB, i.e. when it is still a red (super)giant. Finally, in *Case 3* the last pulse initiates when the star is already in the region of PN nuclei.

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Which one of these various cases will actually apply in a given star is primarily determined by the amount of residual fuel available after the envelope ejection (i.e. by M_{eR}), and by the precise *phase* during the flash cycle at which the superwind terminates. In essence, it depends on whether or not the residual fuel is sufficient for the termination of the cycle initiated with the previous pulse. For instance, if M_{eR} is too small the subsequent increase in core mass will not allow the intershell mass to increase by an amount ΔM_H with respect to the previous pulse, and the star will fail to experience another pulse. As pointed out by Iben and Renzini (1982), almost identical stars could suffer their final pulse under very different circumstances, i.e. will experience a different *Case*. The outcomes of the various cases are now briefly discussed.

Case 1. The final pulse occurs when the star is still on the AGB and has a relatively massive envelope. Correspondingly, the flash is expected to proceed exactly like in the previous pulses, and no major changes are produced in the surface composition. Since, by definition, no further flashes take place during the subsequent post-AGB evolution, the surface composition of PN nuclei produced in this way will be identical to that of the surrounding nebula. Most PN nuclei with spectral type other than WR are probably produced in this way. Note that the sole action of a stellar wind during the post-AGB phase is unlikely to completely remove the residual hydrogen-rich envelope (Renzini 1979, 1981b). Moreover, white dwarfs with hydrogen atmospheres (DA white dwarfs) are also very likely the product of *Case 1* stars.

Case 2. Stars experiencing this case are still in the red giant region but their envelope mass is very low ($M_e \lesssim M_{eR} < \sim 0.01\ M_\odot$). Sackmann (1980b) has computed a flash in a stellar model having these characteristics, and, unlike in normal flashes, the intershell region suffered a runaway expansion. Sackmann does not offer a physical interpretation of this behaviour which, however, is probably due to the following reasons.

In AGB stars the temperature at the top of the carbon-rich intershell region (T_{top}) is subject to large excursions during the pulse cycles. Before a flash T_{top} is of the order of $\sim 10^8$ K, and shortly after a flash it falls to $\sim 10^7$ or less, the precise values depending on M_H. This behaviour is obviously due to the intershell expansion, caused by the sudden injection of energy at the base of the intershell operated by the flash itself. The minimum value attained by T_{top} during a cycle (T^{min}_{top}) is normally higher than the temperature at which carbon is only

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partially ionized. However, when a flash takes place in a star with a low value of M_e, the intershell expansion is somewhat less impeded by the overlying envelope, and thus will proceed futher, i.e. T_{top}^{min} will be somewhat lower.

If, like in Sackmann's model, T_{top} falls below the threshold temperature for carbon recombination ($\sim 3\ 10^6$ K), then a thermal runaway will likely follow. In fact, as carbon starts recombining the radiative opacity dramatically increases thanks to the bound-free transitions of carbon ions. In turn, this increase in opacity will tend to block the radiative energy flux coming from the underlying helium-burning shell, and this energy deposition into the upper intershell region will further assist its expansion causing more and more carbon to cool below the recombination temperature. This chain of physical events can probably account for the runaway expansion of the intershell encountered by Sackmann.

Unfortunately, opacity tables for low-temperature carbon-rich mixtures are not currently available, and the subsequent evolution of *Case 2* post-AGB stars can only be conjectured. Nonetheless, it is likely that the cooler part of the carbon-rich intershell region will become convectively unstable, and will mix with the residual hydrogen-rich envelope. The final surface composition resulting from this type of mixing event will depend on the relative mass of the two merged regions, i.e. M_e and fM_{CSH}, f being the fraction of the intershell which is actually mixed with the residual envelope. Since, in this case, M_e is comparable to M_{CSH}, the surface carbon abundance will become comparable to that of hydrogen and helium, while the N/H ratio will not change.

Note that the runaway expansion initiates once the ordinary flash-driven intershell convection has already disappeared (Sackmann 1980b). Therefore, no further nuclear processing is expected within the newly formed mixed region. Note also that the resulting surface composition is similar to that of some hydrogen-deficient carbon stars (HdC).

The subsequent evolution of the star, once the runaway eventually damps off, will probably proceeds on a nuclear timescale, i.e. the timescale t_b of the helium-burning shell, which is also the time spent by the star at luminosities above $\sim$1000 $L_\odot$. The star will then contract towards the region of PN nuclei, and will eventually become a white dwarf. One can speculate that during the PN phase the star will exhibit a WR spectrum, possibly of type WCN.

Case 3. Finally, the last thermal pulse can take place when the star has already arrived in the region of PN nuclei. Provided this happens when the envelope mass is sufficiently small ($M_e < \sim 10^{-4} M_\odot$, cf. Fujimoto 1977; Schönberner 1979; Iben and Renzini 1982), at the peak of the flash the intershell convection penetrates through the helium-hydrogen discontinuity, engulfing the residual hydrogen-rich envelope. This happens because the entropy barrier between the intershell convection and the envelope is now very small, contrary to the case of AGB stars with extended convective envelopes (cf. Section 2).

The protons captured by the intershell convection are destroyed by the reactions $^{12}C(p,\gamma)^{13}N(e^{+}\nu)^{13}C$, and the resulting ^{13}C can be convected downward towards the hotter layers of the intershell, where it is destroyed by the reaction $^{13}C(\alpha,n)^{16}O$.

The actual calculations of models experiencing these events presents severe difficulties (e.g. the lifetime of ^{12}C and ^{13}C may be comparable to the convective timescale), and, once again, the evolution of the star past the contact mixing can only be conjectured. However, one can reasonably expect that the energy released by the quick burning of the residual hydrogen envelope will cause a macroscopic expansion of the (former) intershell region, and a thermal runaway similar to that described for *Case 2* will probably follow the thermonuclear runaway , if sufficient carbon is cooled below the recombination temperature. Following these events the star is expected to describe a wide loop on the HR diagram, perhaps reaching quite low effective temperatures. Like in *Case 2*, after the damping of the runaway the evolution will probably proceed with a timescale of the order of t_b.

It has been suggested that this picture could account for the origin of R Coronae Borealis stars, as well as of some extreme helium stars and of PN nuclei of type WC (Renzini 1979, 1981b). In fact, the final surface composition (∿75 % He, ∿25 % C, H and N virtually absent) is very similar to that usually reported for these exotic stars. Moreover, about 10 % of all post-AGB stars will probably experience a *Case 3* final flash (cf. Iben and Renzini 1982), and this should also account for the origin of white dwarfs with hydrogen-deprived atmospheres (the so-called non-DA white dwarfs). Finally, the particular cases of the R Cr B star U Aqr and of the PN Abell 30 have been discussed in this theoretical framework (Renzini 1981b).

4. CONCLUSIONS

It has been argued that if the last helium-shell flash occurs *after* the envelope ejection from an AGB stars, then a major change in the stellar surface composition will probably follow. In this case carbon is expected to become a major atmospheric constituent, while hydrogen should be either significantly reduced (*Case 2*), or even totally destroyed (as in *Case 3*). Moreover, such stars are expected to spend a time $\sim t_b$ at high temperatures (> ~30,000 K) and luminosities (> ~1000 $L_\odot$), and it is suggested that the concomitant development of all these conditions should account for PN nuclei of WR type. Futhermore, since t_b is extremely sensitive to M_H (the mass of post-AGB stars), more massive *Case 2* and *3* post-AGB stars will evolve too rapidly following the last flash, and their chance of being observed will be quite low. For instance, for $M_H > 0.9$ the evolutionary time t_b is shorter than about 1000 yr. Therefore, this theoretical picture indicates that the majority of hydrogen-deficient stars (HdC stars, R Cr B stars, WR type PN nuclei, etc.) should have relatively low masses ($0.55 \lesssim M_H \lesssim 0.9$), being then the product of relatively low-mass progenitors ($M_i < \sim 2.5$).

The actual calculation of models suffering *Case 2* and *3* mixing events is affected by several difficulties, but a prerequisite for attempting their modelling is the availability of opacity tables for carbon-rich mixtures at low temperatures (~6000 K < T < 10^6 K).

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DISCUSSION FOLLOWING RENZINI

Wehrse: How sensitive are your results on the abundance changes to the treatment of the outer boundary in view of the fact that the atmosphere of a red supergiant may contain some percent of the total mass and has a very complicated structure?

Renzini: The deep structure of an AGB star is fairly insensitive to the outer boundary conditions, i.e. to the pressure and temperature at the base of the atmosphere. Moreover, changes in the envelope structure produced by using a refined model atmosphere (rather than the crude gray atmosphere employed in stellar evolutionary codes) could easily be balanced by a suitable change in the adopted mixing length.

Shara: In a recent paper in the Ap.J. 247, 225 (1981), Prialnik, Shaviv and Kovetz show that the inclusion of chemical diffusion in the theoretical evolution of a 6 $M_{\odot}$ star prevents thin shell-flashes from ever taking place. Models without this effect included must be taken with several grains of salt.

Renzini: Everything must be taken with grain of salt, including the paper you have just referred to.

Tutukov: Comments: Helium shell flashes in moderate mass stars seem now unavoidable because there are multishell planetary nebulae.
Question: Could you comment the observed chemical composition of the nucleus of FG Sge and its changing with time from point of view of the modern theory?

Renzini: FG Sge could be an example of what I called Case 3. The fact that FG Sge has still hydrogen at the surface should mean that it takes a certain time before the envelope is completely ingested and burnt, which seems quite reasonable. If this picture is correct FG Sge should later evolve into a R Cr B star.

Nussbaumer: You mentioned planetary nebula shell masses of 0.02-1.4 $M_\odot$. There are indications that some shells might have lower masses. Would this upset your picture?

Renzini: The lower limit is set by the nebula in the globular cluster M15, whose mass is particularly well known. For more massive PN precursors I have used the Wood and Cahn semi-empirical determination of M_{PN}. It is worth emphasizing that the dependence of M_{PN} on the initial mass is very uncertain, and could only be determined using all relevant astrophysical constraints. However, one should also remember that only a fraction of the ejected envelope may actually be ionized, especially in young nebulae.

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