Session V

POST–AGB STARS

Michael Feast, as remembered by Pierre North.

POST-AGB VARIABLES AND STELLAR MASS-LOSS

M. W. FEAST
Astronomy Department
University of Cape Town, South Africa

Abstract. A brief review is given of the various types of star which are thought to be in the immediate post-AGB stage of evolution. The paper then concentrates on the properties of the RCB stars and particularly on the mass-loss process in these stars. It is suggested that grain formation takes place over the cool regions of giant convection cells in a super-Eddington outflow and in the form of small clouds or puffs. Attention is drawn to observations which suggest that grain formation in the outer atmospheres of Miras and other cool giants may also take place in puffs rather than in spherical shells. Evidence on the long-term variation of the circumstellar dust emission from RCB stars is summarized.

1. Introduction

A wide variety of objects have been considered as belonging to the post-AGB, pre-PN stage, many of them being variables. The present paper gives a very brief survey of some of these classes of objects. It then concentrates on the R Coronae Borealis (RCB) variables and in particular on what we can learn from them about mass-loss and grain-formation processes. The results suggest clues for the understanding of these processes in cool variables at the tip of the AGB.

2. Criteria for Post-AGB Stars

Amongst the criteria which have been used to assign stars to the post-AGB phase are the following:

1. Unusual surface chemical abundances;
2. Early or intermediate spectral type together with high luminosity and low mass;

R.F. Wing (ed.), The Carbon Star Phenomenon, 207-216.

3. Circumstellar material (gas, dust) indicating earlier and/or current mass-loss (e.g. cool dust, detached shells); and
4. Period changes in pulsating variables indicating rapid evolution to higher temperatures.

However there are several uncertainties in applying these criteria:

1. The luminosities of the objects concerned are often quite uncertain;
2. Low masses are frequently inferred from galactic position or kinematics and this can lead to confusion with, for instance, high-mass stars which are in the region of the galactic halo;
3. The evolution of some objects may have been strongly affected by binary interaction leading to some of the characteristics listed above though the stars are not in the post-AGB phase;
4. It is still uncertain whether bipolar symmetry in circumstellar material is always an indication of binary interaction or whether it might occur in single post-AGB stars; and
5. It is often not clear whether observed period variations are of long-term evolutionary significance.

3. IRAS Sources

An early criterion for post-AGB status was a cold, probably detached, non-variable dust shell as seen in IRAS data (e.g. van der Veen et al. 1989). However, stars undergoing thermal pulsing at the top of the AGB may only become large-amplitude variables (Miras), with high mass-loss, in the bright phase of a thermal pulse. At other times they might well have only low variability together with a detached shell ejected in the Mira phase (e.g. Hashimoto 1994). Good post-AGB candidates are however found by demanding also that the underlying star be a hot (F–G type) supergiant and that there be unusual surface abundances. Stars selected in this way, for example by Kwok (1993) and Hrivnak (1995), are carbon stars showing evidence for both C_2 and C_3. There remains some uncertainty for these objects since some at least (e.g. AFGL 2688) have bipolar symmetry. However, recent HST pictures show that this object has ejected multiple shells, possibly connected to thermal pulsing. Little or nothing is known about the possible variability of these objects.

4. High-Latitude F–G Type Supergiants

This is a heterogeneous group which overlaps with an IRAS-selected sample. These stars are not generally classified as carbon stars although some have enhanced abundances of C, N, and O (Luck 1993; Luck et al. 1990) which suggest a post-AGB status. Of those with such enhancements, the best studied for variability are 89 Her, which is in a spectroscopic binary system, and HD 161796, which is probably single (Waelkens & Mayor 1993; Waters et al. 1993). These two stars show variations of $\Delta V \approx 0.1$ mag on time-scales of 40 to 70 days (e.g. Fernie 1993). Whether these are truly periodic is not certain (they may be similar to the RCB stars discussed below). Radial velocities give no good evidence for radial pulsations in either star (Waelkens & Mayor 1993). Members of a subset of these F–G supergiants have very low overall metallicities. They are interacting binaries and thus not normal post-AGB stars (van Winckel et al. 1995).

5. RV Tauri Stars

The RV Tauri stars are also a rather heterogeneous group although they are all probably radial pulsators. One subgroup (Preston type B) consists of carbon stars. RV Tauri stars generally have strong dust excesses in the IRAS data and often in the nearer infrared too. Jura (1986) modelled these excesses in several cases and found that mass-loss had been much greater (perhaps by a factor of 100) several hundred years ago, consistent with these stars being recent entries to the post-AGB phase and also consistent with the presence of silicate-rich dust shells round C-rich RV Tauris (Lloyd Evans 1974). However, different modelling (Raveendran 1989) suggests a more uniform mass-loss continuing to the present.

Stars of the RVb subclass show long-period, $\sim$1000 day, modulation of their light curves. This is thought to indicate long-period binary motion though the precise mechanism of the modulation is not clear. Several C-rich RV Tauris are in this subclass and have recently been studied extensively by Pollard et al. (1996) using optical photometry. Even RV Tauris which are not in the RVb subclass could still be in binaries. For instance the C-rich star AC Her is classed as RVa (no long-term modulation of the light curve), but radial-velocity work (Waelkens & Waters 1993) indicates that it is in a spectroscopic binary. This suggests that current mass-loss in some, and possibly all, RV Tauris is connected to binary activity and might, for instance, be confined to a disc.

6. RCB Variables

The RCB stars (see Feast 1996, Clayton 1996, and references in these papers) are high-luminosity ($M_V \approx -5$), low-mass objects. In our Galaxy they are strongly concentrated to the galactic centre. They have an overabundance of carbon and a hydrogen deficiency which ranges from at least 10^{-8} to 10^{-1} solar (Lambert & Rao 1994). The RCB class is generally treated as post-AGB although the evolutionary status of these stars (possibly born-again PN or merged white dwarfs) has not yet been finally settled. RCB stars undergo random drops in optical brightness of 7 mag or more and these have long been attributed to dust obscuration. Near infrared observations show an excess attributable to dust at a mean blackbody temperature of 800–1000 K (Feast & Glass 1973). FG Sge, which brightened visually by ~ 6 mag over ~ 100 years as its atmosphere expanded and cooled, changing its bolometric correction, has recently undergone obscuration minima and shows carbon bands indicating that it is now an RCB star or at least a related object (e.g. Kipper et al. 1995).

Photometry and radial velocities show the RCB star RY Sgr to be a radial pulsator with a period of ~ 38 days (Alexander et al. 1972). With its large light amplitude ($\Delta V \approx 0.5$ mag) and evidence for radial pulsations, this star is atypical of the group. However, its pulsation is particularly useful in establishing a number of basic facts regarding RCB stars. Whilst in RY Sgr and other RCB stars outside obscuration minima most of the radiation at optical and nearer infrared wavelengths (i.e. 1.2 μm, J band) comes directly from the stellar photosphere, that at 3.5 μm (L band) and longer wavelengths is mainly from heated circumstellar dust. In RY Sgr the L flux varies in the pulsation period of the star, showing that the pulsating star is responsible for the heating of the dust (e.g. Feast et al. 1977; Feast 1986; Menzies & Feast 1997). During obscuration minima the L observations show that the pulsations go on unchanged, demonstrating that the obscuration has no major effect on the star itself. Also the mean L flux from the shell is unchanged, indicating that the optical obscuration is due to a dust cloud (a puff) of limited size in the line of sight. Obscuration minima of RY Sgr seem normally to begin with a rapid decline, followed immediatedly by a rapid rise to an intermediate brightness. The minima in these initial dips correspond closely with minima in the pulsation cycle as seen at L and give the optical light curve the appearance of a giant pulsation cycle. This effect can be explained as due to the change, during a pulsation cycle, in the size and surface brightness of the outer regions of the star (the "chromosphere") when the main body of the star is hidden by a dust puff (Feast 1996; Menzies & Feast 1997).

The puffs of dust are driven away from the star at, typically, 200 km s^{-1} by radiation pressure. This is shown by absorption lines from gas entrained with the dust. Since our line of sight cannot be presumed special, we expect dust puffs to be ejected randomly in all directions, and in deep minima we see broad (~ 400 km s^{-1}) emission lines which are best interpreted as due to resonance scattering by gas entrained in these puffs (Feast 1996 and earlier papers).

The outer ("chromospheric") regions of RY Sgr are known to be moving outward at ~ 10 km s^{-1}, and the recent work of Asplund & Gustafsson (1996) suggests that this is a super-Eddington outflow. Mass loss can then be seen as a two-stage process: first, low-velocity gas ejection by radiation pressure; then dust formation in this wind, followed by high-velocity dust ejection (also by radiation pressure).

There are a number of constraints on where in the stellar wind the dust grains are formed:

1. The initial declines of RCB stars tend to be rapid (time-scale of a few days) and the recovery times slow (1 to 3 years). Typical light curves can be reproduced if the dust forms as a small cloud relatively close to the star (say at about two stellar radii above the surface). The rapid decline occurs as the puff, moving radially outwards, expands to cover all the star. The slow recovery takes place as the puff gradually thins optically. It is difficult, though perhaps not entirely impossible, to reproduce the light curves satisfactorily if the dust forms far from the star (say 10 stellar radii or more) (Feast 1986, 1996; Clayton 1996).
2. The blackbody temperature of the dust (800–1000 K) suggests that the bulk of the dust is not very close to the star. One can model the infrared colours of dust formed quasi-continuously in puffs which then move rapidly outward. These colours depend on the temperature at which the bulk of the dust forms. Comparison with the extensive infrared photometry of RCB stars extending over more than 20 years (Feast et al. 1997; Feast 1997) shows that $T_{\max} \lesssim 1500\,\mathrm{K}$. This is consistent with the theoretical upper limit for the formation of carbon grains (Salpeter 1977) and with the observed temperatures of carbon-rich material in other sources (see Feast 1997). Such a temperature is only reached at a distance of 10 stellar radii or more above a 6000 K photosphere.
3. The dust forms in puffs rather than spherical shells.

It appears possible to meet these constraints in the following way. Wdowiak (1975) suggested that dust might form in the cool regions of large photospheric convection cells. Whilst it seems unlikely that these could be cool enough, the existence of a super-Eddington outflow suggests that dust formation at the required condensation temperature could take place close to the star in this wind above such cool regions. Such a model then accounts for (1) the production of dust in puffs, (2) the random distribution of puffs over the star, (3) dust formation close to the star, and (4) dust production at the observed (and expected) temperature.

Since the dust forms above dark areas of the disc, this model explains why in general one does not see the molecules (C_2 etc.) which should precede dust formation. However, occasions may occur when the puff covers the entire disc before becoming optically thick. This seems to have been the case for V854 Cen at an obscuration minimum in 1988. One would expect to see strong molecular bands at such times, and these were apparently seen (Kilkenny & Marang 1989; Feast 1997). It might also be expected that in certain conditions molecules would form without subsequent grain formation. When this slowly expanding molecular cloud is projected on the bright areas of the disc, one would see strong molecular absorption near maximum light. Such events were first reported by Espin (1890).

If the convection cell model is basically correct, then we would expect that outside obscuration minima RCB stars will show small-amplitude variations of $\Delta V \approx 0.1$ mag on a time scale of ~ 1 month (see Feast 1996). Variations of this kind are found in most RCB stars. It is still not clear how much of this observed variation is due to the convection cell mechanism and how much to underlying pulsation. Clearly pulsation is a main component in RY Sgr. In many other cases, however, the amplitude of variation is small and the evidence for a regular periodicity is rather weak. Feast et al. (1997) give an example in the case of SU Tau where there was a clear variation of the star in the J band, which might well have been taken for a pulsation cycle, but no variation in the dust flux (at L), strongly suggesting that this was not a global pulsation.

7. Mass Loss at the AGB Tip

Mira variables, both O-rich and C-rich, at the tip of the AGB are losing matter at a copious rate. The process by which they do this is not fully understood although it is of crucial importance in stellar evolution. As with the RCB stars, mass-loss is generally considered as a two-stage process. Gas is raised to sufficient heights above the star to form grains which are then blown away from the star by radiation pressure. The problem has been to understand how the gas is raised to sufficient heights for grain formation. The most promising mechanism for this has seemed to be pulsation, but it is not certain that this can raise gas sufficently (e.g. Wood 1990). However, one might expect that grain formation could, as with RCB stars, take place over the cool regions of the giant convection cells which Schwarzschild (1975) suggested existed in the atmospheres of red giants. Thus the region of grain formation would be much closer to the surface than would otherwise be the case. One then expects this dust to form in puffs. In fact there is considerable direct or circumstantial evidence to support such a model which will lead to surface or circumstellar asymmetries in Mira variables (O- or C-rich). Amongst such evidence is the following:

1. The K I 7699 Å fluorescent emission is highly asymmetrical (Plez & Lambert 1994);
2. The CO distribution around both C- and O-rich Miras is asymmetrical (Stanek et al. 1995);

3. Polarization indicates asymmetry in the scattering dust (e.g. Johnson & Jones 1991, and earlier work);
4. H_2O masers show asymmetrical structure (Yates & Cohen 1994);
5. OH masers in U Her, R Cas, and W Hya show that mass loss is "intrinsically chaotic and clumpy" with the clumps retaining their identity as they move outward (Chapman et al. 1994);
6. The lunar occultation of the C star TX Psc (a long-period variable) shows asymmetry due either to a large cold "spot" on the star or to a dust patch close to the star (Richichi et al. 1995); and
7. Optical interferometry of Miras shows that these stars are frequently non-circular in projection, a plausible explanation being large spots on the surface (e.g. Haniff 1995; Tuthill 1995; Lattanzi et al. 1997).

If this mechanism for the production of dust in Miras is correct we might expect to see RCB-type declines in them. Possibly this is what is being seen in such C-type Miras as R For, as suggested by Whitelock (2000). As yet the data are not available to tell whether this is so or whether the declines of these stars are due to the formation of a complete spherical shell. Similar events in O-rich Miras might be expected to be less evident since, in the optical and near infrared, the extinction cross section of silicate grains is about ten times less than that of carbon grains of the same size.

It is interesting to inquire why we apparently see no RCB activity in C-rich RV Tauri variables. There may be two contributory causes for this. First, it is not entirely clear how high the present mass-loss rate of these stars is. Secondly, as mentioned in section 5, many (at least) of the RV Tau stars are in binary systems, and dust production may in those cases be mainly connected to binary interaction and disc formation.

8. Long-Term Variations in RCB Dust Formation

The extensive infrared photometry of 12 RCB stars for periods extending in several cases over more than 20 years (Feast et al. 1997) has allowed the study of long-term variations in the dust production in RCB stars. In no case is this constant. Several types of variation have been distinguished:

1. Large-amplitude changes in the infrared flux from the dust ($\Delta L \approx 2$ mag) on time scales of from one to several thousand days (e.g. UW Cen, WX CrA, RY Sgr, GU Sgr, RS Tel);
2. Smaller amplitude changes ($\Delta L \approx 0.5$ mag) on a time scale of hundreds of days (e.g. S Aps, V854 Cen, V CrA, RZ Nor);
3. Secular variations ($\Delta L \approx 0.5$ mag) over $\sim$10,000 days (e.g V CrA);
4. Periodic variations; R CrB itself seems to stand alone as showing some evidence of a real periodicity (1260 days) rather than simply a general time scale for variations.

The physical mechanisms behind these various time scales are not understood although ~ 1000 days is the average time between obscuration events in several RCB stars and may therefore be taken as the average time for the renewal of the entire circumstellar environment (Feast et al. 1997).

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Discussion

Cherchneff: You've mentioned large convective cells in which dust could condense. Do you have a feeling for the temperatures of these cells compared to the effective temperature of the star?

Feast: The suggestion is that the dust condenses in the quasi-steady Eddington outflow (which is observed in the ~ 10 km s^{-1} "chromospheric" lines) above cool regions of convection cells, i.e. at ~ 2 stellar radii or so from the star.

Gustafsson: Your proposal that the puffs are related to and triggered by convection cells is interesting. If the downdrafts really cool the gas above them and cause dust formation, one might possibly see tendencies for low-excitation spectral lines in the red to be redshifted (or to have red asymmetrical wings) shortly before the decline, and this redshift would then soon vanish as the downdraft gets occulted. Conversely, if the rising hot granules push the gas across the Eddington limit, the corresponding phenomena should appear in the blue wings of the high-excitation lines. Spectral monitoring of these stars at high resolution could be rewarding.

Asplund: For RCB stars convection occurs in the region of the He ionization, which takes place in rather deep atmospheric layers ($\tau > 10$). Therefore I'm not convinced that large temperature differences due to convection cells still exist on the stellar surface, which has been proposed to cause the dust condensation events.

Feast: Evidently realistic atmospheric models are required. At present I think that the suggestion of large convection cells is quite reasonable. As I said, this predicts low-amplitude variations on time scales of about a month near maximum light, and this may well explain the observed small-scale variations.

Asplund: You also mentioned that before the dust condensation event one expects a strengthening of molecular features. Of course few spectra have been taken immediately before a decline, but in fact this has been observed: the C_2 bands became stronger shortly before a decline in R CrB, as reported by Rao and collaborators at IAU Colloquium 106.

Feast: There is good evidence of essentially neutral-color declines at several minima of RCB stars showing that there was no very strong additional molecular absorption. This does not preclude occasional C_2 production and the "Espin effect."

Magalhães: I would like to comment that when one observes in the IR, one is basically measuring the dust mass, i.e. favoring larger grains. These grains will typically scatter poorly in the optical; here, smaller grains play a role. This would probably have to be taken into account while interpreting IR and optical measurements and inferring where the grains are with respect to the star, as we may be looking at different grains.