ASYMPTOTIC GIANT BRANCH VARIABLES

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ABSTRACT. Asymptotic Giant Branch variables are the brightest and most distinctive individual stars to be found in the resolved, old and intermediate age, stellar populations of galaxies in the Local Group and beyond. The characteristics of these stars are reviewed here with particular emphasis on the luminous AGB stars in the LMC. Most large amplitude variables, both carbon- and oxygen-rich, fall close to a linear extrapolation of the period luminosity relation determined for shorter period Miras. The few such stars which are more luminous than predicted appear to be experiencing extra energy production via hot bottom burning.

Key words: AGB stars, Mira variables, carbon stars, OH/IR stars, hot bottom burning.

1. Introduction

The very first pulsating star on record is Mira itself, now known as *o* Ceti (e.g. Hoffleit 1997). The discovery of Mira as a variable is usually attributed to the Netherlands astronomer, David Fabricius, who noted extreme changes of brightness in 1596, although there are hints that it might have been recognized at even earlier times. Some while later the star was named *Stellar Mira* meaning *the Wonderful Star*, when it was appreciated that its extreme changes in brightness, from visible to invisible, were actually periodic on a time scale of 11 months. We now know Mira Ceti as the prototypical Asymptotic Giant Branch (AGB) variable. Given their long history it is perhaps surprising that the AGB variables have remained such an enigma; they are the most poorly understood of all the recognized classes of variable star - to the extent that even their pulsation modes remains a source of controversy. A visual light curve for Mira Ceti, from amateur observations, is reproduced in AAVSO Report 38 (note that amateur observations remain important in characterizing the behaviour of these very large amplitude variables). The peak-to-peak amplitude, which is typical of these variables, is about 3 mag and the period is 332 days. The behaviour is somewhat erratic with different maxima from one cycle to another; this is quite typical of Mira variables.

Studies of extragalactic resolved populations are becoming both practical and important as we develop not only telescopes in space, but also large telescopes with adaptive optics on the ground. At the same time, advancements in the appropriate array technology is pushing near-infrared observations onto the critical path for understanding of individual stars in these resolved populations. When we examine old or intermediate age populations what we see most clearly are the very brightest individual stars at the very top of the Asymptotic Giant Branch and those are typically the AGB, or Mira, variables. The fact that we are still far from a detailed understanding of these stars, even in our own galaxy, is bound to hinder our attempts to characterize populations in and beyond the Local-Group galaxies.

With this in mind I briefly review below our current understanding of AGB evolution, mentioning dredge-up and hot bottom burning, before looking in more detail at recent observations of AGB variables in the LMC, which provide our first step to more distant populations. *AGB variable* is a term that means different things to different people, but the stars covered here include the Mira variables, mentioned above, OH/IR stars and dusty carbon stars. Where appropriate the lower amplitude, semi-regular variables are also referred to.

The classical defining characteristics of Mira variables are: a large amplitude, emission line spectra (Me, Se or Ce), and periods in excess of 100 days. The OH/IR- and dusty carbon-stars are assumed to be similar to the Miras although they are often too faint at visual wavelengths to determine amplitudes or measure spectra. Their periods are generally long, up to 1000 days for the carbon stars and up to about 2000 days for the OH/IR stars.

2. AGB Evolution

The AGB evolution of low and intermediate mass stars was described by Iben and Renzini (1983); the salient features are outlined below. Stars leave the horizontal branch when they run out of helium in the core; they ascend the AGB burning hydrogen in a shell around an inert C/O core. As the hydrogen burning proceeds a helium shell gradually builds up and will eventually ignite explosively producing a helium shell-flash and starting the phase of evolution known as thermal pulsing; successive shell flashes will occur on time scales of the order of 10^5 years. At the very top of the thermally pulsing AGB the outer atmosphere of the star becomes unstable to pulsations and the Mira variable is born. The Mira pulsations drive mass-loss from the outer atmosphere and most of the hydrogen envelope is eventually lost. Our star then leaves the AGB to cross the HR diagram, becoming first a planetary nebula and then cooling to oblivion as a white dwarf.

The internal structure of an AGB star at the time its atmosphere starts to pulsate is that of an inert C/O white dwarf surrounded by helium and hydrogen burning shells. This core is surrounded by the huge convective hydrogen atmosphere of the red giant and that in turn is surrounded by material of the circumstellar shell. This shell is dominated by dust and molecular effects - showing perhaps Maser emission from SiO, H_2O and/or OH molecules. One of the consequences of thermal pulsing is to allow carbon-rich material from the core to be dredged up into the convective envelope from which it can reach the surface. In this way some stars dredge up sufficient carbon to overwhelm the oxygen and they become carbon stars. At this stage carbon chemistry and carbon dust dominate the stars' observed characteristics.

It is perhaps worth emphasizing that there is no connection between the atmospheric pulsations that give us the AGB variables and the thermal pulsing of the core. The AGB variations occur in the outer atmosphere of the red giant on a time scale of about one year, while thermal pulsing occurs in the core on a time scale of 10^5 years.

To a first approximation the larger the initial mass of a star the higher the luminosity at which its AGB will terminate. Thus the metal-rich Globular Clusters have AGB tips only slightly brighter than the tip of the first giant branch ($M_{bol} \sim -3.7$ mag), while the brightest AGB variables in the LMC, which probably have progenitors of about $M_i \sim 8 M_{\odot}$, are found at about $M_{bol} \sim -7.2$ mag.

For the most part the luminosities of AGB stars are a function of their core mass (Paczyński 1970). However, towards the end of AGB-evolution, for stars with an initial mass in excess of 4 or 5 $M_{\odot}$, the base of the convective envelope can dip into the hydrogen-burning shell, resulting in hot bottom burning (HBB), with far reaching consequences for the evolution of the star. The transition from oxygen-rich to carbon-rich is affected; exactly how seems to depend on the specific model and in particular on how mass loss is treated. HBB may prevent carbon stars happening at all, or prevent them from happening until the envelope mass is depleted (Frost et al. 1998). In some models carbon stars do form and then HBB turns them back into oxygen-rich stars (Marigo et al. 1999). Another consequence, for stars in a rather narrow mass range, is the formation of lithium via beryllium (Sackmann and Boothroyd 1992). One of the most important results in the present context is a rapid increase in luminosity (Blöcker and Schönberner 1991); again the details depend on mass loss which will tend to decrease the effect of HBB. This is obviously very important in terms of the behaviour of the most luminous AGB stars and the apparent observational consequences of HBB are discussed in more detail below.

3. AGB Stars in the LMC

The following discussion and Fig. 1 assume a distance modulus for the LMC of 18.5 mag, for convenience; the best current estimate of the distance modulus is actually 18.58 ± 0.1 mag (Feast 2001). Until relatively recently our knowledge of AGB variables in the LMC was very heavily biased towards large amplitude variables and stars with only thin dust shells. The results of the microlensing surveys and the follow-up work from the IRAS survey has changed the picture considerably during the last decade.

Period luminosity (PL) relations were established by Feast et al. (1989) for carbon- and oxygen-rich Miras in the LMC. They were derived from large amplitude variables monitored over their light cycles to derive mean luminosities. At K ($2.2\,\mu$m) the carbon- and oxygen-rich stars obey the same PL relation, with a scatter of < 0.18 mag, up to periods of around 420 days. Bolometric luminosities were determined by fitting blackbodies to JHK photometry - a reasonable approximation for those stars which have only very thin dust shells. The bolometric PL relations appeared to be different for the oxygen- and carbon-rich Miras, although it was never clear if this was really so, or an artifact of the way the bolometric luminosities were derived.

Groenewegen and Whitelock (1996) derived a bolometric PL relation for LMC carbon Miras using all the spectroscopically confirmed carbon stars, although there were only single epoch observations for many of them. Their PL relation was essentially indistinguishable from that for oxygen-rich stars. At the time this work was done no LMC carbon Miras were known at periods significantly longer than 500 days, and the optically visible longer period oxygen-rich stars lay clearly above an extrapolation of the PL relationship for short period stars. As discussed below this is quite possibly because they are experiencing extra energy production via HBB.

Smith et al. (1995) performed a survey for lithium among AGB stars in the SMC and LMC. They found that a very large fraction of those with bolometric magnitudes in the range $-6 \lesssim M_{bol} \lesssim -7$ were lithium rich, as were a much smaller number of lower luminosity stars. Our present understanding of lithium enhancements in AGB stars is that most of them occur as a result of HBB as described in section 2 above.

According to Sackmann and Boothroyd (1992) lithium enhancements are to be expected in stars with initial masses around 4 or 5 $M_\odot$, the exact value depending on metallicity. In view of this it is interesting to note that a very large fraction of the stars which fall above the PL relation must be undergoing HBB, as their high lithium abundance indicates. Note that in fig 6 of Smith et al. (1995) the PL relation runs through the low luminosity ridge line of the points. A few of the brighter star will be SR variables which we would expect to lie above the Mira PL relation and some others almost certainly have erroneous periods. Furthermore, the luminosities of all these stars require more detailed investigation, most are based on single observation of large amplitude variable.

As we would expect to detect enhanced lithium only from a fraction of the stars actually experiencing HBB it is possible to speculate that all of the stars with luminosities above the PL are there because of HBB. It is perhaps important to remember that the stars investigated by Smith et al. are not representative of AGB stars generally; they are the brightest ones with the thinest dust shells, as it was only practical to obtain spectra, with sufficient resolution to measure the lithium lines, of that subgroup.

A group of people with whom I have been working (see, e.g. van Loon et al. 1999b) have, over the last few years, obtained ground-based and ISO data of about 50 thick-shelled LMC sources originally selected from the IRAS data-base. We have also been able to derive periods for many of them. By combining ground-based, $JHKL$, photometry with ISOCAM and ISOPHOT photometry and spectroscopy it has been possible to derive luminosities by fitting models to the combined dataset. Because the ISO observations do not cover the light cycle and most of the energy is emitted longward of 5 μm we should expect a lot of scatter in the results. Carbon- and oxygen-rich stars were distinguished on the presence or absence of the 3 μm, $C_2H_2 + HCN$, feature which is a very clear diagnostic of carbon-rich chemistry (van Loon et al. 1999b and references therein). A PL diagram of the results is shown in Fig. 1.

Seven of the stars in Fig. 1 are common with the sample discussed by Wood (1998), and some of the long-period oxygen rich stars are OH/IR stars. Although our periods agree very well with those derived by Wood, the luminosities (van Loon et al. 1999b) do not, and five of the six carbon stars we find to be considerably brighter than he did (Whitelock and Feast 2000a). The Groenewegen and Whitelock (1996) relation for carbon stars extrapolates between the two lines shown in Fig. 1. In interpreting this figure it is crucial to remember that the luminosities illustrated here are one-off measurements of large amplitude variables, because we have, in general, only single epoch ISO observations. Where points are joined together they represent separate observations of the same star at different phases. It has to be clear from this that a good deal of the scatter in this diagram is due to variability. It is also clear that the bulk of these stars, both oxygen- and carbon-rich, fall close to the extrapolated PL relation for oxygen-rich variables.

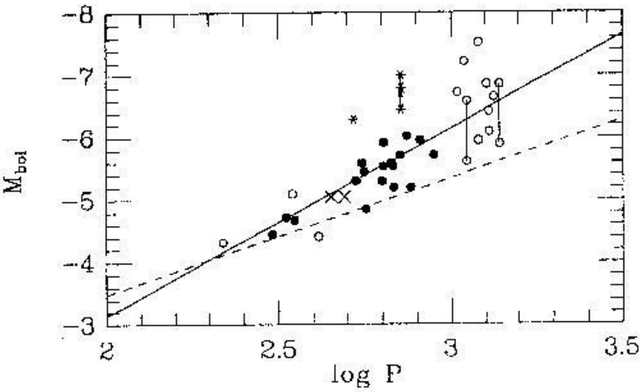

Figure 1: The PL relation for long period AGB stars in the LMC. The luminosities are from van Loon et al. (1999b) and are single phase measurements. The periods are from Whitelock et al. (in preparation). The solid and broken lines are extrapolations of the PL relations, determined by Feast et al. (1989), for oxygen- and carbon-rich stars, respectively. Solid symbols represent carbon stars and open ones oxygen-rich stars. The stars marked as asterisks are IRAS 04496–6958 and SHV F4488 which are both carbon-rich (but see text). Connected points represent measurements of the same star at different epochs. The crosses represents carbon stars in LMC clusters and their luminosities and periods are from Nishida et al. (2000).

4. Some Interesting Individual Stars

Figures 2 and 3 illustrate K light curves for two of the LMC carbon stars. These particular examples combine SAAO data with Wood's published observations to give very good light curve coverage - over a time interval of 5 to 6 years. With an 830 day period TRM 4 is one the longest period carbon stars in our sample, and indeed one of the longest period carbon stars known. The peak-to-peak amplitude is almost 2 mag at K. The other star, TRM 88, has a somewhat shorter period and lower amplitude, although it has a very marked secular or long period variations on top of the pulsation. The net result of this is an effective peak-to-peak amplitude of about 2 mag. This type of erratic behaviour is quite common among mass-losing carbon stars both in the LMC and in the Galaxy. It is

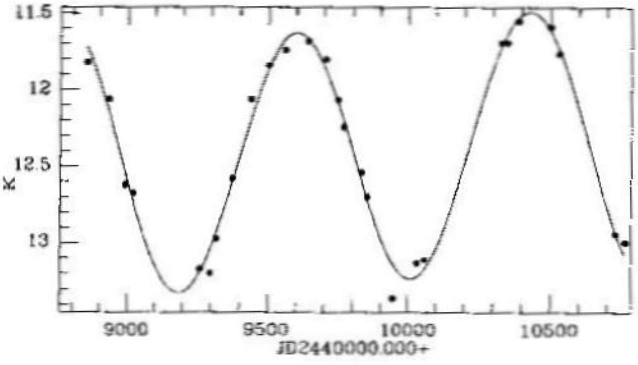

Figure 2: The light curve of carbon star TRM 4, using data from Wood (1998) and Whitelock et al. (in preparation). The curve is a sinusoid of period 830 days together with a long-term trend.

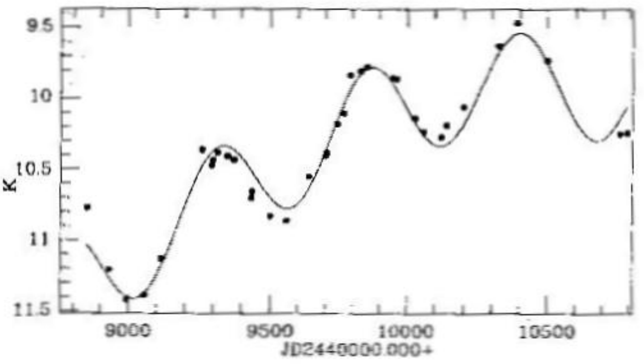

Figure 3: The light curve of carbon star TRM 88, using data from Wood (1998) and Whitelock et al. (in preparation). The curve is a sinusoid of period 543 days together with a long-term trend.

probably caused by variations in the mass-loss rates.

It is difficult to put an accurate figure on the bolometric amplitudes of these stars as very little monitoring has been done at wavelengths beyond 4 μm. The best we can do (see van Loon et al. 1998) is look at the individual ISO measures we have for these LMC sources together with 10 μm repeated measures of Galactic sources by Le Bertre (1992) and by Harvey et al. (1974). This leads to an estimate of a bolometric amplitude for the carbon stars of a little under 1.0 mag peak-to-peak and for the oxygen-rich stars with periods over 1000 days between 1.0 and 1.5 mag.

Returning again to the PL plot in Fig. 1, The asterisks represent luminous carbon-stars at which we will take a closer look. For IRAS 04496–6958 there are four independent measures of the luminosity (from van Loon et al. 1998, 1999a, 1999b) as indicated in the figure. Its 3 μm spectrum shows the clear signature of the $C_2H_2 + HCN$ carbon-star feature, but its 10 μm ISO spectrum (Trams et al. 1999) is very unusual - showing a feature which indicates the presence of both silicates, which suggest an oxygen-rich shell, and silicon carbide, which suggests a carbon-rich shell. It is therefore the first extragalactic example of a carbon star with silicate emission. There are several Galactic stars which show a similar combination of oxygen- and carbon-rich features. They are generally understood to be binary systems in which silicate dust surrounds the binary of which one component is a carbon star (Lloyd Evans 1990). It may be that the same explanation applies here, although in view of its high luminosity Trams et al. offered an alternative explanation - that it was, until recently, a star undergoing HBB - hence the silicate dust. It would thus be an example of a star in which HBB terminated, perhaps due to mass-loss, and which then underwent a thermal pulse and dredge-up, turning it into a carbon star.

The other high luminosity carbon star in Fig. 1, SHV F4488, was noted by Smith et al. (1995) as lithium rich. Our luminosity is considerably higher than that used by Smith et al. ($M_{bol} = -6.3$ mag compared to -5.7). This might be due either to variability or possibly to the flux used by Smith et al. being underestimated, as they had no information on the contribution from mid-infrared wavelengths. In any case we can presume the star is undergoing HBB and it is interesting to see that lithium and carbon enrichment can coincide at these high luminosities. So it would appear that even among the carbon-stars the most luminous examples show signs of HBB.

There have also been some recent discoveries of obscured carbon stars in Magellanic Cloud star clusters, which are particularly interesting because we know something about their ages and metallicities. Nishida et al. (2000) have published periods for three such stars, two of which are in LMC clusters. These are marked as crosses on the PL diagram of Fig. 1. They seem to be quite comparable to the obscured field-carbon-stars. These two clusters have turn-off masses of around 1.5 $M_{\odot}$. This initial mass for 500 day carbon Miras is very similar to that found in a recent study of obscured AGB variables in the solar neighbourhood, by Olivier et al. (2001). They estimate that both the carbon- and oxygen-rich stars, with periods in the 400 to 800 day range have masses between 1 and 2 $M_{\odot}$. They also estimate the initial masses of OH/IR stars with periods over 1000 days at around 4 $M_{\odot}$. The same may be true of the obscured LMC stars under discussion, although it is difficult to say with certainty.

5. Other AGB Variables

Wood (2000) discusses the PL relationship (his fig. 1) for LMC variables found from the Macho data-base. He assumes, probably reasonably, that those stars with redder $J - K$ colours are carbon-rich. Most of the stars he describes are more luminous than the tip of the giant branch and are therefore clearly on the AGB. What he finds are four (perhaps five) PL relations running approximately parallel to each other. The luminosities are derived from single observations and therefore show a certain amount of scatter.

The large amplitude variables fall close to the Mira sequence, which is identical to the one discussed above, but so do some of the smaller amplitude variables. Two sequences at shorter periods contain variables with smaller amplitudes and another sequence is seen at longer periods. Wood interprets this diagram as demonstrating that fundamental pulsators lie on the Mira sequence, while the shorter period sequences mark the positions of overtone pulsators. Of course we know nothing about the relationship of the stars in the various sequences to each other and it is possible that their differences are in more than pulsation mode. The origin of the fourth, long period, sequence is unclear, although Wood discusses various possibilities.

If Miras pulsate in the fundamental mode, which seems possible, we must still explain why their diameters, which have many optical and near-IR measurements, imply that they are overtone pulsators (e.g. Whitelock and Feast 2000b).

6. Conclusions

Observations of AGB variables in the LMC show the following:

1. Those which are close to the end of their AGB lifetimes fall close to the Mira PL relation.
2. Carbon- and oxygen-rich Miras obey the same PL as well as we can establish with the available data.
3. Many, perhaps all, of the *large amplitude* variables which lie above the PL relation are undergoing hot bottom burning.
4. The sequences of variables identified from the Macho data show pulsation in a variety of modes, and indicate that we are far from fully understanding AGB variables even in our nearest galaxy.

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