Infrared Observations of Large Amplitude Pulsating Stars

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Abstract. Our understanding of large amplitude pulsating stars and their status in stellar evolution is briefly reviewed. The paper then describes the near-infrared light curves of various asymptotic giant branch stars, concentrating on possible evidence for changing mass-loss rates. The stars discussed include oxygen- and carbon-rich Miras, OH/IR stars, thick-shelled carbon stars and symbiotic Miras. Finally a newly discovered Mira variable in the Sagittarius Dwarf Galaxy is described.

1. Introduction

The following discussion concentrates on asymptotic giant branch (AGB) stars, including both classical Miras and the longer period infrared sources which seem to be closely related to the Miras. Although many supergiants also fall in the large amplitude variable category they are not considered here. The Miras have large amplitudes by definition; their visual magnitude range exceeds 2.5 mag, although IR and bolometric amplitudes are usually smaller. They are long period, mostly in excess of 100 day and have spectra dominated by molecular absorption with hydrogen lines in emission at certain phases (Kholopov et al. 1985, GCVS). The infrared variables overlap in properties with the Miras, but their periods extend to over 2000 days. They have very late spectral types and although they are often too faint to have measured visual amplitudes, near-IR amplitudes of a magnitude or more are common (e.g. Whitelock, Feast & Catchpole 1991).

2. Stellar Evolution

We understand these stars to be near the end of their AGB evolution (Iben & Renzini 1983). Their next evolutionary move will be across the HR diagram to become white dwarfs, possibly via a planetary nebula phase. Chemical enrichment, in particular the presence of technetium (Merrill 1952; Little et al. 1987) tells us that many of them are on the thermally pulsing AGB and experiencing third dredge-up. From the strong thermal infrared flux we deduce that they are losing mass copiously and are probably in the super-wind evolutionary phase identified by Renzini (1981). They obey a period-luminosity (PL) relation (e.g. Feast et al. 1989; Whitelock et al. 1994) making them potentially useful distance indicators. The longer period, higher luminosity stars presumably had a higher initial mass than their short period counterparts although there is probably not
a one-to-one relationship of period to initial mass across the whole period range. At the short period end, 200 day Miras are found in metal-rich globular clusters (Menzies & Whitelock 1985) so we know more about them than the others. As expected, the kinematics of the short period Miras differ from those of the longer period stars (Feast 1963; Whitelock et al. 1994).

3. Pulsation and Mass loss

A number of interesting theoretical papers have appeared recently concerning the connections between pulsation and mass loss. Of particular note are those by the Vienna group (e.g. Höfner, Feuchtinger & Dorfi 1995) and by the Berlin group (e.g. Fleischer, Gauger & Sedlmayr 1995), both of whom describe and model the dust-induced $\kappa$-mechanism which leads to the periodic formation of dust and creation of shock waves in material flowing outwards from a mass-losing star. Thus a theoretical framework for the interpretation of accurate light curves has become available for the first time. One paper in particular, Winters et al. (1994), makes detailed predictions of the IR light curves of mass-losing carbon stars. Their models predict the periodic formation of dust on a timescale which is generally some multiple of the stellar pulsation period. Thus their predicted light curves show the results of the superposition of two oscillations, that of the interior pulsation and that produced by the dynamical structure of the circumstellar dust shell. More recently, Höfner & Dorfi (1997) have pointed out that the behaviour of the dust is not periodic for most of their models. This seems important as it is more consistent with the observations which are described below.

4. Observations

The IR (broad-band $JHKL$) photometry discussed below was obtained with the MkII IR photometer on the 0.75-m telescope at SAAO, Sutherland. The results are part of a long-term monitoring programme started by Michael Feast over 20 years ago. All measurements are on the SAAO system as defined by Carter (1990).

| Table 1. Variable Stars |
|-------------------------|
| Star | Sp type | Period (day) | $\Delta K$ (mag) | $\dot{M}$ ($\times 10^{-7} M_\odot yr^{-1}$) | symbol |
| S Ind | M | 400 | 0.8 | 2 | $\triangle$ |
| R Cae | M | 398 | 0.8 | 2 | $\triangle$ |
| IK Tau | M | 470 | 1.0 | 50 | $\circ$ |
| OH 327 − 0.6 | M | 600 | 1.2 | 60 | $\circ$ |
| R For | C | 389 | 0.9 | 8 | $\bullet$ |
| IZ Peg | C | 486 | 2.0 | 200 | $\bullet$ |
| R Aqr | Sym | 387 | 0.8 | 6 | $\times$ |
| RR Tel | Sym | 387 | 0.9 | 30 | $\times$ |
Figure 1. The IR colours of the stars listed in Table 1 and discussed below. The symbols are defined in the table.

It is particularly useful to work in the 1 to 4 $\mu$m region when dealing with AGB variables, first, because they are cool stars whose stellar energy distributions peak in the IR, so that we are examining the behaviour of the bolometric output rather than minor fluctuations in the temperature; secondly, the $J$ and $L$ light curves respond rather differently to the effects of increased dust in the stellar atmosphere. The stars whose light curves are illustrated below have IR colours which suggest the presence of circumstellar shells and hence moderate to high mass-loss rates.

The stars under discussion are listed in Table 1 and their mean colours are illustrated in a two-colour diagram (Fig 1). Their spectral types (Sp), pulsation periods (P), $K$ amplitudes ($\Delta K$) and approximate mean mass-loss rates ($\dot{M}$) are also tabulated. The sample comprises: two oxygen-rich Miras with periods around 400 day, S Ind and R Cae; two much redder longer period OH/IR Miras, IK Tau and OH327 – 0.6; two carbon stars, the bright Mira R For and a dust-shell source, IZ Peg, with a somewhat longer period and much redder colours; and finally there are two oxygen-rich symbiotic Miras, R Aqr and RR Tel, with periods around 400 day. The two oxygen-rich Miras have the bluest colours and therefore the thinnest shells. All of the other colours show the clear signature of reddening, presumed to be circumstellar. Only OH327 – 0.6 is in the Galactic Plane and thus may experience some interstellar reddening, but its bright apparent luminosity suggests it is close, so even there the major cause of the red colours must be circumstellar extinction.
5. Light Curves

5.1. O-rich Miras and OH/IR Stars

Figure 2 illustrates the $J$ and $L$ light curves for the two oxygen-rich Miras, $J$ and $L$ being the two extreme wavelengths on the SAAO monitoring programme. The data shown here span over 22 yr. Regular pulsations are clearly evident at both wavelengths, with those at the shorter wavelength having the larger amplitude, as is normal for most pulsating stars. You can also see in both figures the same kind of erratic irregularity that characterises the visual light curves of Miras (e.g. the AAVSO curves shown in Whitelock 1996); cycles do not repeat exactly from one to the next and there are trends on a variety of longish time scales. Notice in particular that when the $J$ curve fades so does the $L$ curve; although the amplitude is smaller at $L$ the behaviour is qualitatively identical. S Ind and R Cae also have remarkably similar light curves and specifically similar long-term variations.

Still with the oxygen-rich variables, Fig 3 illustrates the light curves of the longer period stars IK Tau (NML Tau) and OH327.4−0.6, which are both bright OH Masers (Wilson & Barrett 1972; Caswell & Haynes 1975). Larger amplitude variations are evident at $J$ than at $L$. The $J$ curves show clear long-term trends in opposite directions for the two stars; IK Tau is fading and OH327.4−0.6 brightening. Although in both cases $L$ follows the same long-term trend as $J$, it does so at a much lower amplitude. This is in contrast to the previous two stars. These trends are probably produced by changing dust obscuration, although it is possible that changes in the stellar temperature could produce the effects. A comparison of the long-term IR behaviour with that at other wavelengths would be instructive as would a detailed comparison with model predictions.

5.2. Carbon Variables

IZ Peg (CRL 3099) was too faint at $J$ near minimum light for reliable photometry with the 0.75-m telescope, therefore $H$-band photometry is illustrated in Fig 4. Its extreme colours are the consequence of a thick circumstellar shell and strong circumstellar reddening. Its light curve is very similar to that of OH327.4−0.6, being fairly regular with some gradual long-term trends. R For on the other hand, also illustrated in Fig 4, shows rather more dramatic changes in its $J$ light curve. It is in this respect typical of other carbon stars, with moderate dust shells, e.g. R Lep and R Vol, which have been monitored from SAAO. These stars show changes of $\Delta J \sim 2$ mag on time-scales of a few years. The analysis of these data is discussed elsewhere (Whitelock et al. 1997; Whitelock 1997) and will therefore be described only briefly here.

The $J$ light curve for R For, after the normal Mira pulsations have been removed, is illustrated in fig 3 of Whitelock (1997). What we see in this residual curve are changes in obscuration of the star, apparently as a consequence of the erratic production of dust. Whitelock et al. showed that it is possible to model the brightening event around JD 2446000 as the consequence of an expanding cloud of dust formed 500 $R_\odot$ from the star and moving with a velocity of 20 km s$^{-1}$. This dust ejection cannot have been spherically symmetric or the fading at $J$ would have been accompanied by brightening at $L$, which it was not. The changes between JD 2447000 and 2450000 could be explained as the effects
Figure 2. The $J$ and $L$ light curves for R Cae and S Ind from 1975 to 1997.
Figure 3. The $J$ and $L$ light curves for IK Tau and OH327.4 $- 0.6$ from 1979 to 1997.
Figure 4. The $J$ and $L$ light curves for R For from 1975 to 1997 and the $H$ and $L$ curves for IZ Peg from 1979 to 1997.
of a number of overlapping dust ejections. The dust might thus be ejected as puffs in random directions as it is in RCB stars (Feast 1997). In which case the star will ultimately acquire a patchy, but essentially spherically symmetric, shell. Alternatively, the dust might be ejected preferentially into a torus or disk which, to explain the R For observations, would have to be in our line of sight. The torus model would help explain the rather low apparent luminosities measured for stars like R Lep (van Leeuwen et al. 1997; Whitelock et al. 1997).

5.3. Symbiotic Stars

Particularly good light curve coverage has been obtained for several symbiotic Miras. These binary stars, comprising a Mira interacting with a white dwarf, offer us a somewhat different perspective on the mass-loss problem and we should recall that there must be many unidentified binary systems among the catalogued Miras. The symbiotic Miras are also known as $D$-types, D for dust, because their IR colours are clearly modified by the presence of dust (Webster & Allen 1973; Whitelock 1987) obscuring the Mira. Their optical and ultraviolet spectra are dominated by high excitation emission lines, such as HeII and [OIII]. These lines are excited in a circum-binary nebula formed during mass transfer between the two stars. Thus the presence of the Mira only makes itself felt at long wavelengths and the existence of a cool star in symbiotic systems only became clear following IR observations. The orbital periods of these stars are unclear but generally thought to be of the order of decades (Whitelock 1987).

R Aqr, which is by far the best studied symbiotic Mira, is a bright star associated with an obvious and extensive reflection nebulosity. It is also associated with what is sometimes described as a jet, which is bright both at ultraviolet and at radio wavelengths. The Mira has a pulsation period of 387 day, and is unusual among symbiotic Miras in that it, and not the hot component, dominates the optical light. The Mira PL relation, the Hipparcos parallax and geometrical arguments all imply a distance around 200 to 250 pc (Whitelock 1987; van Leeuwen et al. 1997; Hollis, Pedelty & Lyon 1997). Willson et al. (1981) suggested a binary period of about 44 yr on the basis of dips seen in the AAVSO light curve, interpreted as eclipses (see also Whitelock et al. 1983). The “eclipse” would be caused by an orbiting dust cloud obscuring the Mira. One of these “eclipses” corresponds to the fading seen in Fig 5 around JD 2443000. The depth of the “eclipse” exceeds two mag at $J$, but reaches only about one mag at $V$. The later part of Fig 5 looks like a normal Mira light curve. There are the usual apparently erratic differences from one light cycle to another, but nothing as dramatic as the “eclipse”.

The second part of Fig 5 shows another symbiotic Mira, RR Tel, which is also a very slow nova. It first gained notoriety with its outburst in 1944, when it apparently brightened by 7 or 8 mag in the visual. It was initially thought that the Mira had disappeared in the event, but IR observations again made it clear that the Mira was essentially unaffected by the white dwarf outburst (Feast et al. 1977; 1983). However, there are some peculiarities of the Mira. It is somewhat redder than you would expect for a star with a 387 day period. It is a high latitude source at $b = -32^\circ$, so presumably the reddening is circumstellar. Interestingly, it also shows what might be an “eclipse” in the $J$ light, around JD 2447500. However, this event is followed by a lot of irregularity, another dip
Figure 5. The $J$ and $L$ light curves for the symbiotic Miras R Aqr and RR Tel from 1975 to 1997.
around JD 2449000 and possibly another one in progress at the moment. This is much greater irregularity than was evident at earlier times. It is also interesting to see that $L$ does not fade with $J$, but actually brightens a little later. It is probably significant that we see these “eclipses” or obscurations events in all symbiotic Mira that have been monitored for more than about 10 yr; they have not been properly explained as yet (Whitelock 1987). Their spectral signature certainly suggests dust, but is it new dust ejected from the Mira, as we think is occurring for the carbon stars, or is it old dust in orbit, as has been suggested for R Aqr? We really need other types of monitoring over similar long time scales to sort out what’s going on in these stars.

6. Miras in the Sagittarius Dwarf Galaxy

I would like to finish by showing the light curve of a newly discovered Mira in the Sagittarius dwarf galaxy. The Sagittarius dwarf was discovered in 1994 by Ibata, Gilmore & Irwin (1994). It is at a distance of only 25 kpc from the sun being about 16 kpc behind the Galactic Centre. It appears to be undergoing tidal disruption and to be in the process of merging with the Milky Way. It contains planetary nebulae (Zijlstra & Walsh 1997) and at least one carbon Mira (Whitelock, Irwin & Catchpole 1996). This is a particularly useful variable as it provides us with the only carbon Mira outside of the LMC with a well determined distance. Fig 6 illustrates its $K$ light curve phased at the period of 300 day. The amplitudes of the variations are $\Delta J = 1.0$ mag, $\Delta H = 0.7$ mag and $\Delta K = 0.4$ mag; there can be no doubt that this is a large amplitude variable. The distance modulus derived from these observations and the Groenewegen
& Whitelock (1997) PL relation is $17.14 \pm 0.25$ mag (with essentially all the uncertainty coming from the spread in the PL relation). This can be compared with the distance modulus of $17.02 \pm 0.19$ mag which Mateo et al. (1995) derive from the horizontal branch. There are several other luminous and red carbon stars in the Sgr dwarf which we are monitoring from SAAO and which may well be large amplitude variables.

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11
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