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Long-period variables

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Abstract. Some recent advances and current problems related to the long-period variables are discussed. In particular, some new theoretical results are discussed, as are some possible interpretations of the variables on the multiple period-luminosity relations exhibited by red giant stars

Key words. Stars: late-type – Stars: variable – Stars: binaries – Stars – oscillations

1. Introduction

The discovery of the multiple period-luminosity sequences for red giant variables in the Magellanic Clouds (Wood et al. 1999) gave a major boost to the study of long-period variables. Many subsequent studies using MACHO, DENIS and OGLE time series observations (Wood 2000a; Cioni et al. 2001; Ita et al. 2004; Soszyński et al. 2004; Groenewegen 2004; Fraser et al. 2005) have refined the initial results of Wood et al. (1999). Reviews in this volume by Kiss and Soszyński describe these observations. In this contribution, I will concentrate more on theoretical modelling of the long-period variables.

2. The nature of objects on the period-luminosity sequences

2.1. Pulsating variables

Wood et al. (1999) showed that the shorter period sequences A, B and C of variable red giants could be explained by radial pulsation in the few lowest order modes. The stability of higher order modes seems to be quite distinct, since there appears to be a well defined short period edge to the sequences at a given luminosity. The reason for this is almost certainly that higher order modes have frequences above the accoustic cutoff frequency in the surface layers of these stars (Lattanzio and Wood 2004). In this situation, any kinetic energy of pulsation developed by driving mechanisms in the interior will leak out through the photosphere via travelling waves rather than be reflected back into the interior to create a standing wave. The approximate position where this happens in the period-luminosity diagram is shown in Fig. 1, where the accoustic cutoff frequency for an isothermal atmosphere $(\gamma\mu m_{\rm H}/kT)^{1/2}g/2$ has been used. The models used are those shown in Wood et al. (1999) and the temperature is the boundary temperature $T_{\rm eff}/2^{1/4}$. Given the simplicity of the models and the approximation for the cutoff frequency, it does appear likely that the accoustic cutoff frequency defines the shortest period self-excited oscillations in red giants.

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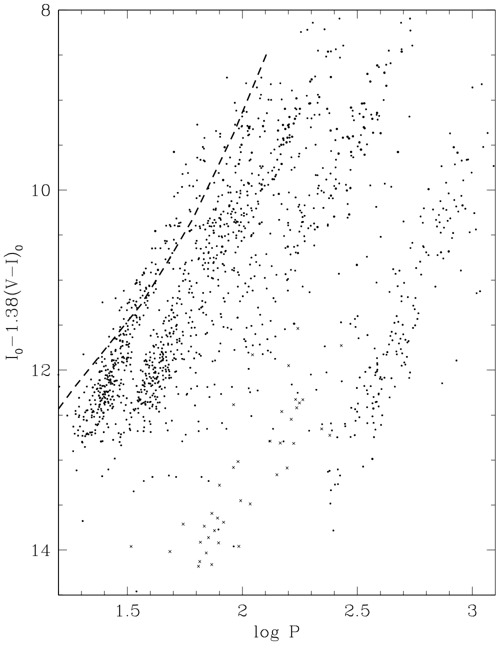

Fig. 1. The period-luminosity sequences for LMC red giant variables in the MACHO database from Wood et al. (1999). The dashed line shows the position where the pulsation period equals the accoustic cutoff frequency in the surface layers of the star.

2.2. Sequence D stars

Wood et al. (2004) have studied spectral and radial velocity variations of the variables on sequence D. Radial velocity variations have also been studied by Hinkle et al. (2002). The main observational facts about these stars are:

- The stars fall on a period-luminosity sequence, roughly parallel to the radial pulsation sequences;
- There is usually a shorter period (or periods) present in these stars, corresponding to one of the radial overtone modes. The sequence-D period is therfore often referred to as a long secondary period;
- The stars show radial velocity variations at the photometic period, with a full amplitude of ~5 km s^{-1};
- The radial amplitude of these stars is large, amounting to ±20−30% of the mean stellar radius;
- The stars show large variations in the strength of the H_α absorption line, with a period equal to that of the photometric variations. Given the coolness of the photospheres of these stars ($T_{\rm eff}$ ~ 3000 K), the existence of H_α absorption indicates the presence of a chromosphere. The central depth of the H_α absorption indicates that the chromosphere covers up to 50% of the star at some phases of the long secondary period.

At the present time, the origin of the long secondary periods in sequence-D stars is unknown. These periods are some four times longer than the radial fundamental mode period, so they can not be due to a normal radial mode oscillation. Other pulsation possibilities are some sort of strange mode (Wood 2000b) or nonradial *g*-modes. However, the strange modes are extremely damped and current theory would not predict them to be seen. In addition, the shorter radial overtone periods in these stars would be expected to vary in length through the long secondary period. This does not occur, providing further evidence against the possibility of radial pulsation. The large amplitude of the oscillations is a major problem for the *g*-modes which should be confined to the radiative surface layers which are only one or two percent of the stellar radius.

Binary models for the sequence-D stars have the problem that the merger timescale for the red giant and its companion is of the order of 1000 years, whereas some 25% of AGB stars show long secondary periods, indicating a lifetime of $\sim 10^5$ years. The orbital circularization timescale is estimated to be of similar length, yet the velocity curves are quite asymmetric which would indicate a non-circular orbit in a binary scenario. The general similarity of the radial velocity curves of the sequence-D stars is also a problem for any binary model.

More detailed considerations of these and other possible explanations for the long secondary periods of sequence-D stars are given in Wood et al. (2004).

2.3. Sequence E stars

The sequence-E stars have always been assumed to be binary systems (Wood et al. 1999). Wood et al. (1999) showed that the examples they found lay on the first giant branch in the case of low mass stars, or the equivalent pre-core helium burning giant phase of intermediate mass stars. Soszyński et al. (2004) have recently used OGLE data to study a larger sample of these stars, showing that sequence E extends up the AGB. They also showed that the P-L relation for the sequence-E variables, which they identify as ellipsoidal variables, crosses the sequence-D P-L relation i.e. these two relations appear to have a different slope. Most interestingly, they note that a subclass of the sequence-E stars have light curve shapes that are consistent with eccentric orbits, contradicting the theoretical expectation noted above for the sequence-D stars.

Radial velocity variations a small sample of sequence-E variables in the LMC are currently being collected (see the paper by Adams et al. in this volume). The velocity variations are a few tens of km s^{-1} as expected for low mass red giants with close companions and the observed periods. Preliminary light curve modelling indicates that the sequence-E red giants may have masses similar to their core masses, indicating that they may be the result of some sort of common envelope evolution.

3. Nonlinear pulsation models

A long-standing problem with modelling the nonlinear pulsation of red giant stars has been that the models appear much more violent in their behaviour than real stars. A recent advance in this area is the addition of turbulent viscosity to the models, which has finally allowed more realistic nonlinear models to be produced (see Olivier and Wood (2005), and Olivier and Wood in this volume).

The new models allow an examination of the question: Are the periods and average $T_{\rm eff}$ values of large amplitude Mira variables similar to those of a static star of the same mass, luminosity and composition? Ya'Ari and Tuchman (1996) found that a number of 1 $M_\odot$ red giant models that they pulsated for long intervals of time (several hundred years) underwent dramatic *decreases* in period due to structural rearrangement. On the other hand, Wood (1995) found that a 1 $M_\odot$ model with $L = 4000L_\odot$ *increased* its period from 209 days in the small amplitude pulsation regime

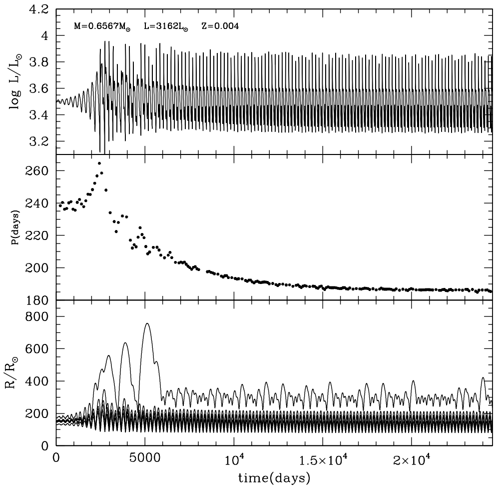

Fig. 2. Luminosity L, Period P and Radii of various mass zones plotted against time for a low mass red giant with $M = 0.6567M_\odot$ and mean luminosity 3162 $L_\odot$.

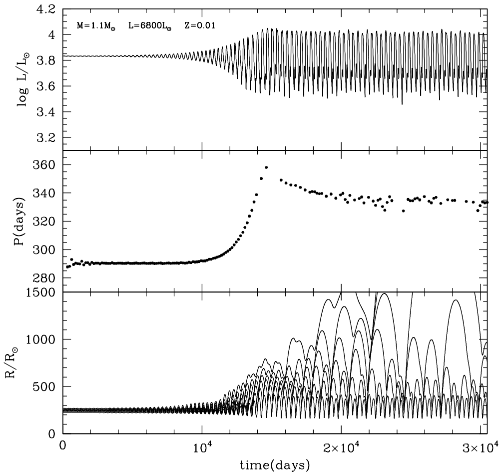

Fig. 3. Luminosity L, Period P and Radii of various mass zones plotted against time for a red giant with $M = 1.1M_\odot$ and mean luminosity 6800 $L_\odot$.

to P = 243 days at full nonlinear amplitude, although the full amplitude $\Delta M_{\rm bol} \sim 1.3$ mag. is about twice the typical amplitude for a star of this period (Feast et al. 1982). The new models with turbulent viscosity allow an examination of models with appropriate amplitudes (the turbulent viscosity parameter can be adjusted to give an amplitude near to the observed values).

Fig. 2 shows the period change experienced by a model with a very low envelope mass when it reached full amplitude. This star clearly underwent a large decrease in period. Lebzelter and Wood (2005) invoked such period changes as necessary to explain the periods of the Mira variables in the globular cluster 47 Tuc (see also Lebzelter and Wood in this volume).

The above results do not appear to hold for more massive stars. Fig. 3 shows the period variation in a star of mass 1.1 $M_\odot$ as its amplitude increases. This star undergoes an *increase* in period as the amplitude increases, in contrast to the behaviour shown by the very low mass object. The amplitude and sign of these period changes clearly needs investigation, especially in view of the increasingly accurate angular diameter measurements that are now being made for Mira-like variables.

In the solar vicinity, a number of Mira variables are known to have double-humped light curves e.g. R Cen. Such stars have been noted to occur among the more massive ($M \sim 5$ $M_\odot$) and luminous ($L \sim 30000$ $L_\odot$) long-period variables in the LMC e.g. HV 2576. By analogy with Cepheids, it was thought that these stars might get their double-humped light curves from a resonance between the fundamental mode and an overtone mode. A number of nonlinear pulsation series for these stars have been run, and it appears that modal resonance is not involved: all the models show the double-humped light curves regardless of luminosity and mass. An example of such model is shown in Olivier and Wood (2005). In Fig. 4, a model made explicitly to replicate the behaviour of the long-period variable HV 2576 is shown. This model clearly shows double-peaked behaviour, and reproduces the K light curve, but it does not reproduce the visual light curve at all well. It is uncertain whether this is due to inadequacies in the pulsation models of in the conversion from L and $T_{\rm eff}$ to V.

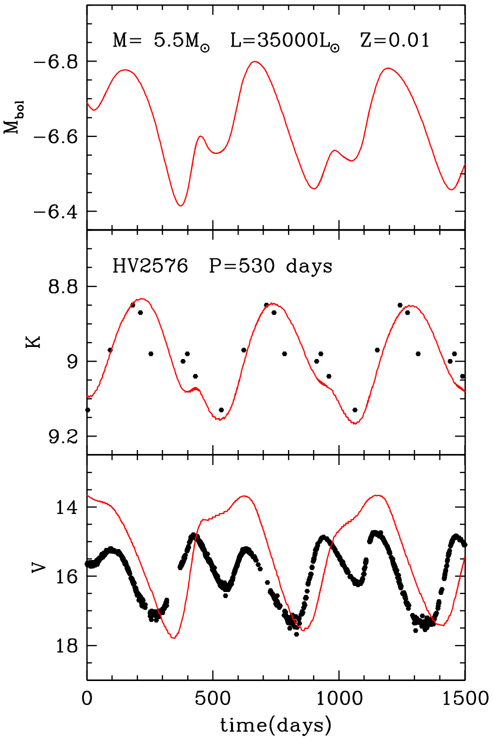

Fig. 4. A nonlinear pulsation model for the Harvard Variable HV 2576. The model has $M = 5.5 M_\odot$ and mean luminosity 35000 $L_\odot$. The K and V light curves for HV 2576 are shown as points while the model results are shown as continuous lines. The V light curve is derived from MACHO observations.

An interesting feature of the model for HV 2576 is the behaviour of the outer layers. In Fig. 5, the velocity of selected zones is shown. It can be seen that in the outer layers, there are multiple bounces of zones falling back onto the star. The amplitude of these bounces is varies from 15-40 km s^{-1} (depending on the phase) and should be easily observable.

4. Conclusions

Improved observations of Magellanic Cloud and Bulge variables by experiments such as OGLE are improving our understanding of the long-period variables, as are observations

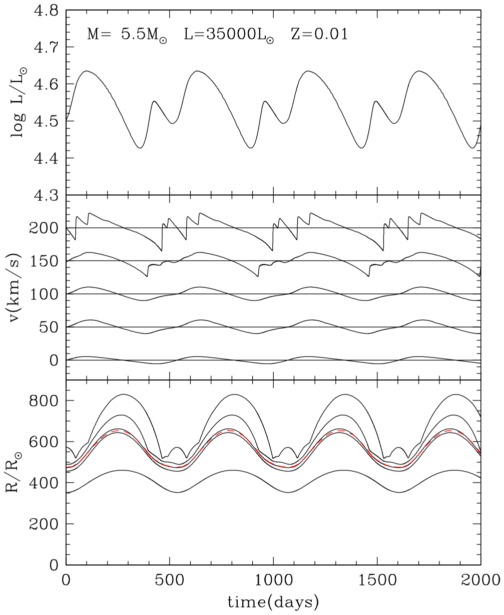

Fig. 5. Variation of the luminosity and the velocities and radii of selected mass zones in the model for HV 2576. Each velocity curve is offset from its neighbour by 50 km s^{-1}, with zero velocity shown by a hozizontal line for each zone.

of spectra and velocities. Nonlinear models construction has been improved by adding new physics to the models. Both these factors should lead to improved understanding of the long-period variables and to a solution of some outstanding problems such as the origin of the sequence-D variability.

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