

# Variability in Binary and Single Red Giants

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# Declaration

This thesis is an account of research undertaken between August 2007 and June 2011. Except where indicated below or in the text of the thesis, the work is that of the candidate alone.

Chapters 2 to 4 have been published as papers, and Chapter 5 is a paper in preparation. A list of authors, and, where appropriate, publication details, are given at the beginning of each chapter.

**Chapter 2:** The spectral monitoring was undertaken by P. R. Wood and M.-R. L. Cioni. I. Soszyński provided the OGLE III light curves prior to their public release. The standard star spectra were taken by P. R. Wood, who also constructed the model of the pulsating semiregular variable and wrote the code FITALL that was used in part of the analysis. P. R. Wood also contributed some of the text. The candidate cleaned the sample, calculated the radial velocities, checked for zero point errors, and did the analysis. The bulk of the paper was written by the candidate.

A preliminary analysis of the LSPVs was submitted as part of the candidate's Honours thesis. However on commencement of the PhD the previous results were entirely re-derived and the project was significantly extended. No part of the preliminary write-up appears in the published paper.

**Chapter 3:** The visual inspection of MACHO light curves to select a clean sample and the K-S tests were done by the candidate. The bulk of the analysis and writing was done by P. R. Wood. The paper is included here for completeness.

**Chapter 4:** The spectral monitoring was undertaken by P. R. Wood and M.-R. L. Cioni. The candidate cleaned the sample, calculated the radial velocities, checked for zero point errors, and did most of the analysis. Work on the mid-IR excess of sequence E stars was done by both the candidate and P. R. Wood, who wrote Section 4.3.1. The rest of the paper was written by the candidate.

**Chapter 5:** The spectra were taken by both the candidate and P. R. Wood, as part of a long-term monitoring project instigated by P. R. Wood. The candidate reduced the data, calculated the radial velocities, modelled the systems using the Wilson–Devinney code, and did the analysis. P. R. Wood contributed some text to Section 5.3.1. The rest of the paper was written by the candidate.

Further acknowledgements are given at the end of each chapter.



Christine Nicholls  
September 2011



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# Abstract

Variable red giants populate several sequences in the period–luminosity plane. Most sequences represent radially pulsating variables, but two sequences show more enigmatic behaviour. Sequence D is populated by stars known as Long Secondary Period Variables (LSPVs). Two forms of variation are evident in their light curves, the first of which is an overtone pulsation lying on one of the shorter-period pulsation sequences. The cause of the Long Secondary Period (LSP) has not yet been successfully identified. Many models have been proposed for the elusive LSP cause, including radial and nonradial pulsation, binarity, and orbiting dust clouds. Sequence E consists of stars with small light amplitudes, regular periods, and the symmetric variations characteristic of close binaries. They are speculated to be ellipsoidal variables on the basis of their light curves, although radial velocity curves are necessary to confirm this.

Here we study these two groups of red giant variables, the inscrutable LSPVs and the sequence E binaries.

First, we present a sample of LSPVs analysed using new radial velocity curves from VLT spectra, alongside MACHO and OGLE light curves. We find the LSP radial velocity variation is too large for radial pulsation, as it implies a fractional radius change of  $> 30\%$  over the LSP. These large radius variations are not accompanied by correspondingly large amplitudes in  $T_{\text{eff}}$  or light, making radial pulsation an unlikely LSP cause. However, the sample’s velocity amplitudes show a striking similarity, and small values for binary motion, implying small and similar companion stars,  $\sim 0.09M_{\odot}$ . Companions of this mass are thought to be extremely rare. Additionally, the angles of periastron indicate surprisingly similar orbital orientations, unexpected in a sample of binaries. Therefore binarity also seems to be ruled out as an explanation for the LSPs.

The mid-IR colours of LSPVs show they have a significant mid-IR excess compared to stars without LSPs, at both 8 and 24  $\mu\text{m}$ . This indicates the LSP is associated with enhanced circumstellar dust. We also find that the near-IR  $J - K$  colour of LSPVs is unaffected by the 24  $\mu\text{m}$  excess. This suggests the circumstellar dust is in a disk or clumpy configuration. Although dusty disks could be associated with binarity, the problems with the binary explanation, described above, remain.

We present two samples of sequence E binaries. Using the first, we show that their combined MACHO light curves and VLT-derived velocity curves constitute unambiguous evidence that sequence E stars are ellipsoidal variables. By comparing the phased light and velocity curves of LSPVs and sequence E variables, we show that LSPs are not caused by ellipsoidal variability, and that these two variable types are fundamentally different. Sequence E stars show no evidence of a mid-IR excess that would indicate excess circumstellar dust, unlike the LSPVs.

Our second sequence E sample is comprised of stars with light curve shapes believed to denote eccentric orbits. We confirm their eccentric nature and model the OGLE light curves and observed radial velocity curves using the Wilson–Devinney code, obtaining complete system parameters. Most of our eccentric sequence E star light curves have unequal maxima as well as minima, a phenomenon not observed in non-eccentric sequence E variables. We find evidence that the shape of the ellipsoidal red giant changes throughout the orbit, due to high eccentricity and the varying influence of the companion. The complete solutions obtained for these systems will allow future modelling to determine how eccentricity is maintained in these and other evolved binaries.

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# Introduction

## 1.1 The Life and Times of Red Giants

Low to intermediate mass stars spend the majority of their life on the main sequence, burning hydrogen to helium in their cores. Main sequence stars are relatively compact and spherical, with low luminosity. Compared to this relatively sedate period of a star's life, its later evolution is much more exciting.

A star leaves the main sequence when it exhausts the supply of hydrogen in its core. The core begins to contract and increase in temperature, while the outer layers of the star expand. The star becomes a red giant for the first time, ascending the red giant branch (RGB), also known as the first giant branch. Here it burns hydrogen in a shell around its helium core. On the RGB, a  $1 M_{\odot}$  star may have a radius of up to  $\sim 100 R_{\odot}$ , a temperature of  $\sim 4000$  K, and a luminosity of up to  $\sim 3000 L_{\odot}$  (Bertelli et al., 2008). The bulk of its volume is made up of its convective outer layers, while about half of its mass resides in its relatively small, dense core. Due to its lower temperature, it is much redder than it was on the main sequence.

Eventually the increasing mass and pressure on the helium core, from the shell burning hydrogen to helium above it, causes the helium core to ignite. For low mass stars ( $M \lesssim 1.85 M_{\odot}$ ) this ignition happens abruptly and degenerately, in a core helium flash. Intermediate mass stars ( $1.85 M_{\odot} \lesssim M \lesssim 8 M_{\odot}$ ) ignite their helium core non-degenerately and more calmly. The star moves from the RGB tip to the horizontal branch or red giant clump (low mass stars) or the core helium burning loops (intermediate mass stars) where it burns helium to carbon and oxygen in its core (Karakas, 2010).

Once the core helium is exhausted, the outer layers expand as the star ascends the giant branch for the second time, as an asymptotic giant branch (AGB) star. It now burns hydrogen and helium in shells around the carbon and oxygen core. On the AGB, a  $1 M_{\odot}$  star has a radius of up to  $\sim 300 R_{\odot}$ , a luminosity of up to  $\sim 4000 L_{\odot}$ , and a temperature of  $\sim 3000$  K (Bertelli et al., 2008). The inflated and tenuous convective atmospheres of red giants give them low surface gravities, with  $\log g \sim -1$  to 1.

Each consecutive nuclear burning phase in a star's life is shorter than the last, and the time a  $1 M_{\odot}$  star spends on the AGB will be  $\sim 10^7$  yr in comparison to its  $\sim 10^{10}$  yr main sequence lifetime (Vassiliadis & Wood, 1993). The number of stars observed in each evolutionary phase is proportional to the time spent in that phase,

so many fewer AGB stars are observed than main sequence stars.

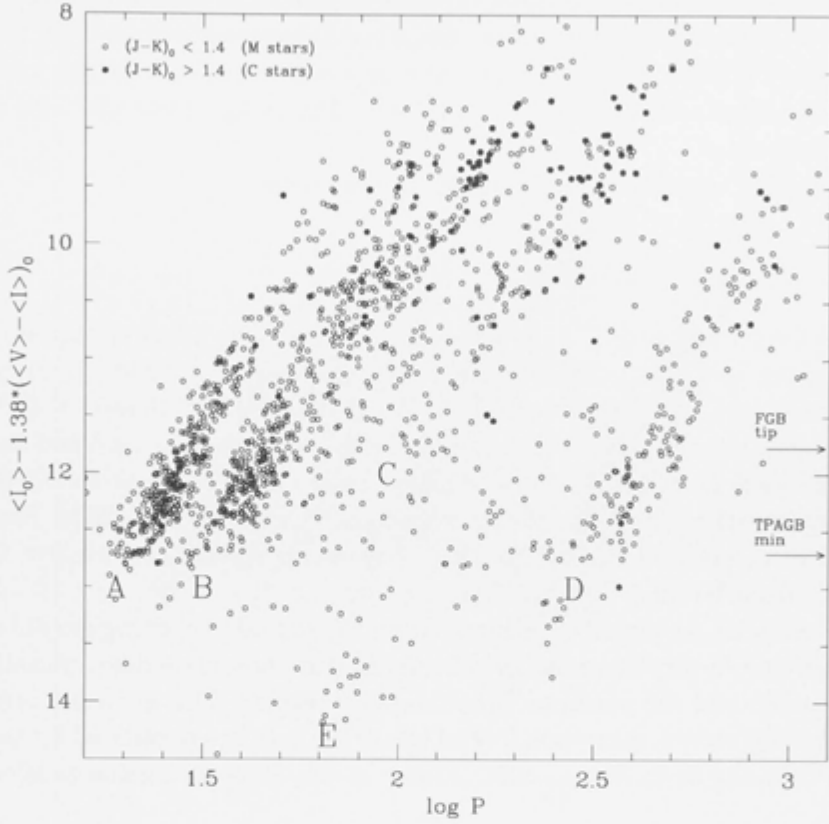
Red giants, and AGB stars in particular, show curious and fascinating behaviour. On the upper AGB, stars undergo instabilities of their helium burning shells that result in changes to the surface composition. A good review is given in Karakas (2010). In simple terms, the intermittent burning of the helium shell, known as ‘helium shell flashes’ or ‘thermal pulses’, cause occasional extinguishing of the hydrogen-burning shell, and temporary convective mixing between the shells. The convective envelope is then able to mix this intershell material, enriched in carbon and s-process elements, to the stellar surface in a process known as Third Dredge Up (TDU). If enough thermal pulses occur before the star loses its envelope, the surface can become so enriched in carbon that the ratio of carbon to oxygen exceeds unity, turning the star to a carbon star.

Stars can lose a significant amount of mass as red giants, usually via a stellar wind similar to that shown on the main sequence, only much slower and denser. The amount of mass lost increases with luminosity, and on the AGB mass loss can be as high as  $10^{-4} M_{\odot} \text{ yr}^{-1}$  (Vassiliadis & Wood, 1993; Groenewegen et al., 2007). It is thought that this higher mass loss rate is a result of the combination of pulsation and radiation pressure on grains (Wood, 1979; Höfner, 2011). The mass lost by AGB stars that have experienced TDU events makes a major contribution to the chemical enrichment of the interstellar medium.

Large amplitude variability is another common phenomenon observed in red giants, usually due to radial pulsation. All stars become variable once they reach the AGB, and are known as Long Period Variables (LPVs), as they have significantly longer periods than other pulsating stars, such as Cepheids and RR Lyraes. The most well-known LPVs are the luminous, high amplitude Mira variables. LPVs are important tools for studying many aspects of astronomy, as the relationship between their period and luminosity, and the fact that they are luminous enough to be observed in galaxies outside our own, mean they can be used to measure extragalactic distances. They can also give direct mass estimates of AGB stars, using the pulsation mass (e.g. Kamath et al., 2010; Lebzelter & Wood, 2011).

## 1.2 The Period–Luminosity Diagram for Variable Red Giants

The large-amplitude, bright Mira variables have long been known to form a period–luminosity sequence (Feast et al., 1989), much like the well-known Cepheid distance scale discovered by Leavitt (1908). Wood & Sebo (1996) examined LPVs in the Large Magellanic Cloud (LMC), and discovered the existence of a second period–luminosity sequence. They identified the sequence containing Mira variables as the fundamental mode of radial pulsation, due to the large Mira amplitudes and the good agreement of the observed sequence with theoretical pulsation models of the fundamental mode. They further suggested that the second sequence, lying at shorter periods, most likely represented stars pulsating in the first or second radial overtone mode. Bedding & Zijlstra (1998) also found a second sequence, in the



**Figure 1.1:** Period–Luminosity diagram from Wood et al. (1999). The y-axis is an almost reddening-free luminosity index. Periods are in days.

period–luminosity diagram of LPVs in the solar neighbourhood.

The advent of large photometric surveys and CCD accuracy hugely increased the numbers of known variable stars with well-determined light curves. Using observations of LMC red giants from the Massive Compact Halo Objects (MACHO) microlensing survey, Wood et al. (1999) found not two but five different sequences in the period–luminosity plane. These multiple sequences have since been observed in other photometric surveys such as OGLE (the Optical Gravitational Lensing Experiment), EROS (Expérience de Recherche d’Objets Sombres), and DENIS (DEep Near Infrared Survey of the Southern Sky); in the Small Magellanic Cloud (SMC) and in the Galaxy as well as the LMC (Ita et al., 2004; Soszyński et al., 2004a; Cioni et al., 2004; Fraser et al., 2005, 2008; Soszyński et al., 2007). In Wood et al. (1999)’s original diagram, sequences were identified by letters, as shown in Figure 1.1.

The different LPV period–luminosity sequences are now known to represent different types of red giant variability. Sequence C and those at shorter periods correspond to different radial pulsation modes. However sequences D and E show variations that are markedly different. As Wood et al. (1999) noted, sequence E stars have regular periods and symmetric light curves, unlike all other LPVs. They

suggested sequence E stars were contact binaries on the RGB and in the core He burning loops of intermediate mass stars. Sequence D represents stars with Long Secondary Periods (LSPs), where the primary period is a radial overtone pulsation that lies on sequence B of Wood et al. (1999). The cause of the LSP was not immediately apparent.

All these variable types are now discussed in more detail.

### 1.2.1 Pulsating Variables

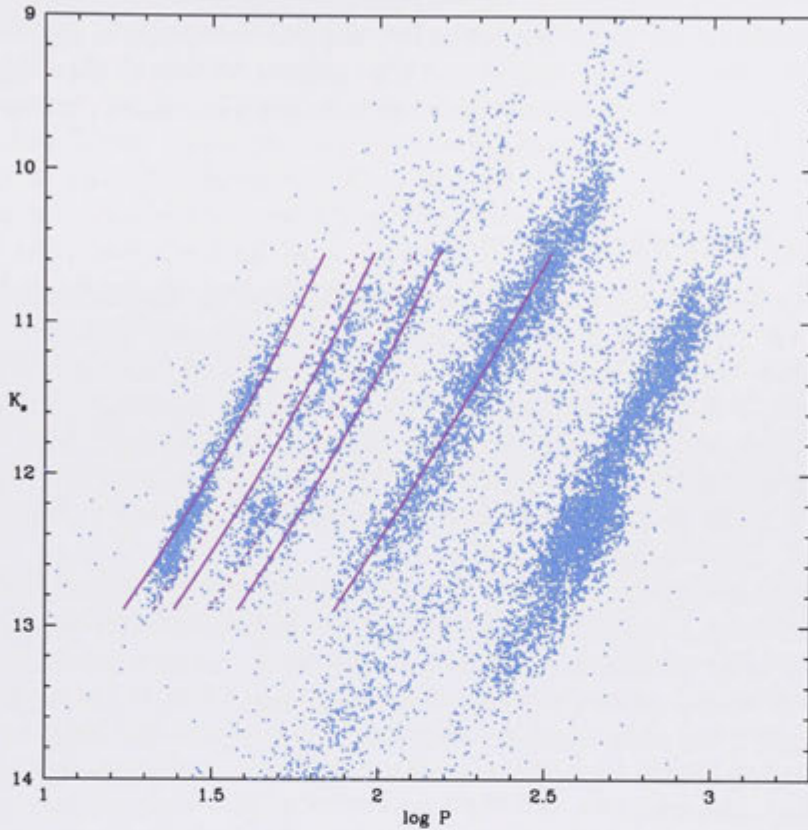
Mira variables fall on sequence C in Wood et al. (1999)'s plot, a fact confirmed by the presence of the largest amplitude variables on this sequence, though variables with smaller amplitude are found there too. Wood et al. (1999) showed that the sequences falling at shorter periods than C may be fit by the first, second and third radial overtone mode pulsations. There has since been some debate as to whether sequence A can indeed be fit by a radial overtone mode (e.g. Ita et al., 2004; Fraser et al., 2005), but a modified mixing length in convection models may resolve this (see Figure 1.2, from Wood & Arnett, 2011).

As one moves to longer period sequences within the radially pulsating part of the red giant period–luminosity diagram, in general the stars become redder, pulsation amplitudes increase and the pulsation becomes more regular. This is an indication that lower pulsation modes, corresponding to longer periods, are populated by more evolved stars (Vassiliadis & Wood, 1993; Fraser et al., 2008; Lebzelter & Wood, 2011).

Subsequent investigations have found finer structure within the period–luminosity diagram. Ita et al. (2004) discovered that in larger samples, sequence B splits into two sequences (see Figure 1.2). They retained the name ‘B’ for the sequence closest A, and proposed the name ‘C’ for the sequence lying between B and C. Soszyński et al. (2004a) analysed the multiperiodic variations of small amplitude, short period red giants they labelled OSARGs (OGLE Small Amplitude Red Giants), and found four sequences both above and below the tip of the red giant branch (TRGB) luminosity. These correspond to A, B, C, and a sequence on the shorter period side of A which was previously unknown. Derekas et al. (2006) also found this shortest-period sequence, known as A’.

Ita et al. (2004) found an obvious discontinuity at the TRGB in sequences A and B. They divided A and B into A+ and A–, and B+ and B– (where ‘+’ denotes the sequence above the TRGB and ‘–’ that below). They hypothesised that the ‘+’ sequences were composed of metal-rich, intermediate age AGB stars, and that the ‘–’ sequences were a blend of old metal-poor AGBs, and RGBs. The sequences below the TRGB luminosity lie at slightly longer periods than those above, and Ita et al. (2004) suggested this was a result of the temperature difference between AGB and RGB stars at the TRGB luminosity, as predicted by stellar evolution models such as those of Castellani et al. (2003). Soszyński et al. (2004a) also observed the discontinuity, and agreed that the sequences below the TRGB contained many RGB stars, based on their observations of different pulsational properties between AGBs and RGBs. Tabur et al. (2010) also find the discontinuity in the MACHO data.





**Figure 1.2:** The period–Luminosity diagram for LMC AGB stars from Fraser et al. (2008) (blue points), and models of the first six radial pulsation modes calculated using modified mixing length theory (magenta lines). Solid lines represent unstable modes and dotted lines represent stable modes. Periods are in days.

The period–luminosity relations of LPVs show little dependence on metallicity. Ita et al. (2004) claimed their data showed that LMC Miras were fainter than (lower-metallicity) SMC Miras of the same period. However Glass et al. (2009) found no difference between the slopes of red giant period–luminosity relations in the LMC and the Galaxy, and Tabur et al. (2010) found that the zero points of LPV period–luminosity relations for the LMC, the SMC and the Galaxy were no different, despite the known metallicity differences between these populations.

Several authors have commented on the differences between the period–luminosity relations for O-rich and C-rich red giants (Feast et al., 1989). Fraser et al. (2005) noted that most carbon stars were found at the high-luminosity ends of sequences C and C'. Riebel et al. (2010) divided the MACHO sequence C variables into O-rich, C-rich, and highly reddened ‘extreme’ AGB stars, and examined the period–luminosity relations in several infrared (IR) bands from 2MASS (the Two Micron All Sky Survey) and SAGE (Surveying the Agents of a Galaxy’s Evolution). They found that in a given band, the period–luminosity relation is steepest for the

extreme AGB stars, and steeper for the C-rich objects than the O-rich objects. They also find the dependence of the period–luminosity slope on wavelength is greater for more evolved objects, which are redder and thus brighter at longer wavelengths. They found that O-rich AGB stars and RGB stars do not show much dependence of period–luminosity slope on wavelength.

### 1.2.2 Long Secondary Periods

Stars with LSPs were first discovered several decades ago by Payne-Gaposchkin (1954) and Houk (1963), when they made up  $\sim 1.5\%$  of known LPVs. When Wood et al. (1999) identified them as one of the sequences in the red giant period–luminosity plane, it became clear that the phenomenon was much more common than previously suspected. Wood et al. (1999) found these sequence D stars, also known as Long Secondary Period Variables or LSPVs, make up  $\sim 25\%$  of AGB stars, and more recent studies have suggested the fraction may be as high as 50% (Soszyński et al., 2007; Fraser et al., 2008).

Although the mechanism responsible for producing the LSP is unknown, several of its properties are apparent from the light curves. The length of the LSP varies, but is in general  $\sim 8$  to 10 times longer than the primary period, which has been shown to be a radial overtone pulsation generally lying on sequence B or C' (Wood et al., 1999). LSP length is anywhere between  $\sim 250$  and 1400 days, and the variation can have a range of amplitudes, although the LSP is significantly larger in amplitude than the primary pulsation.

LSP light curves are typified by asymmetric and non-regular variations in which both periods are usually clearly visible. The LSP variation has been observed to fade away and/or reappear, the LSP minima often vary in depth, and period changes on the timescale of the LSP are common. However the primary period does not seem to be affected by the presence of the LSP.

Many attempts have been made to uncover the cause of this mysterious, slow, large-amplitude variation. Wood et al. (1999) suggested the asymmetric shape of the light curve, the range of observed amplitudes, and the fact that they populate a period–luminosity sequence indicates that the LSP is most likely the result of an eclipse of the AGB star by a dusty cloud surrounding a small binary companion. Such a dust cloud would have a comet-like shape according to the SPH simulations of Theuns & Jorissen (1993).

Hinkle et al. (2002) examined the light curves of eight Galactic LSPVs and confirmed that the LSP appeared in radial velocity variations for six of the stars. Using IRAS colours they found two of their LSPVs showed no evidence of an IR excess, and the remaining stars showed only a small IR excess, suggesting the LSP could not be the result of dust obscuration or mass loss. They derived orbital elements from the velocity curves of their six LSPVs, which showed very small and similar velocity amplitudes, and almost identical eccentricities and angles of periastron. They noted that if the LSP minimum is due to an eclipse, it should align with superior conjunction as indicated by the velocity curve, yet it was not observed to do so. From these results and the extremely small derived companion

masses, Hinkle et al. (2002) stated that LSPVs were unlikely to be binaries as their properties were drastically different to a comparison sample of field AGB binaries. However they admitted their velocity curves were often sparse, and that the primary pulsation made the data difficult to analyse. Nevertheless they proposed that the cause of the LSP was pulsation in a yet to be discovered mode.

Olivier & Wood (2003) showed that spectral line broadening in LSPVs is no greater than in variables without LSPs. Their measured line widths indicated that LSPV rotation velocities must be less than  $3 \text{ km s}^{-1}$ , at which speeds it is difficult to reproduce all but the very longest LSPs, meaning the LSP is probably not the result of stellar rotation. They also found similar IRAS mid-IR colours for LSPVs, non-LSPVs, and some R Coronae Borealis (RCB) stars, which experience sudden, irregular fading events caused by formation of dust. This confusing result left them unable to state whether dust in LSPVs was more enhanced than in non-LSPVs. However they did find LSPVs to have larger radial velocity variations than pulsating red giants, and interpreted it to mean the LSP is caused either by binarity or pulsation.

In the most thorough LSPV study prior to that described in this thesis, Wood et al. (2004) analysed light and velocity curves for three LSPVs. They examined several models for LSP cause, including radial pulsation, nonradial pulsation, binarity, rotation of a distorted red giant, dust ejection, and star spots. They found all these models had significant problems. Radial pulsation was ruled out on the basis that theory dictates the existence of no modes with periods longer than the fundamental mode, and that the observations showed no significant variation in  $T_{\text{eff}}$ . Nonradial pulsation modes with periods matching LSPs exist, but Wood et al. (2004) explained these should not have significant amplitudes in convective atmospheres, and thus could not produce the observed radial velocities. Both radial and nonradial modes were ruled out by the apparent lack of variation of the primary period over the long secondary cycle. Like Hinkle et al. (2002), Wood et al. (2004) also noted the striking similarity between velocity curves of different LSPVs in their sample, and the resulting statistical implausibility that they were binaries. They found variations in the  $H\alpha$  and Na D line profiles, indicating variation of chromospheric activity and mass loss with the LSP. Wood et al. (2004) conceded that LSPs could be caused by a nonradial  $g^+$  mode pulsation combined with large star spots, but only if AGB stars have thicker radiative layers in their atmospheres than is currently believed.

Soszyński et al. (2004b) found that sequence E overlaps sequence D, when E is plotted at twice the light curve period, as is correct under the assumption that sequence E stars are ellipsoidal variables (see Section 1.2.3). They suggested this could indicate a common cause for at least some of the sequence D and E variables.

Derekas et al. (2006) also plotted sequence E at the orbital period for ellipsoidal variables, but delved further into the differences between the light curves of sequence D and sequence E variables. They compared light amplitude as a function of  $K$  magnitude for sequences D, E and C, and found the correlation shown by LSPVs was different to both that of the ellipsoidals and of the fundamental mode radial pulsators. They also found the ratio of MACHO blue amplitude to red amplitude as a function of period for LSPVs was more like the correlation found for sequence

C than that for sequence E. From this they concluded that since LSPVs showed greater similarity to the pulsating stars than to the binaries, the LSPs were more likely to be caused by pulsation.

Soszyński (2007) found 5% of LSPVs had an ellipsoidal variation at the period of the LSP, by subtracting the LSP amplitude ratio found by Derekas et al. (2006), with the aim of cancelling the LSP from the light curves. They argued that this was evidence that the LSP is related to binarity, but stressed that the LSP is clearly not directly caused by ellipsoidal variability. They proposed a similar model to that of Wood et al. (1999), of a binary involving a mass-losing AGB star and a small companion, possibly a planet that had accreted mass lost from the star to become brown dwarf size (Retter, 2005).

It was clear at the start of this thesis that more study was needed to uncover the cause of LSPs.

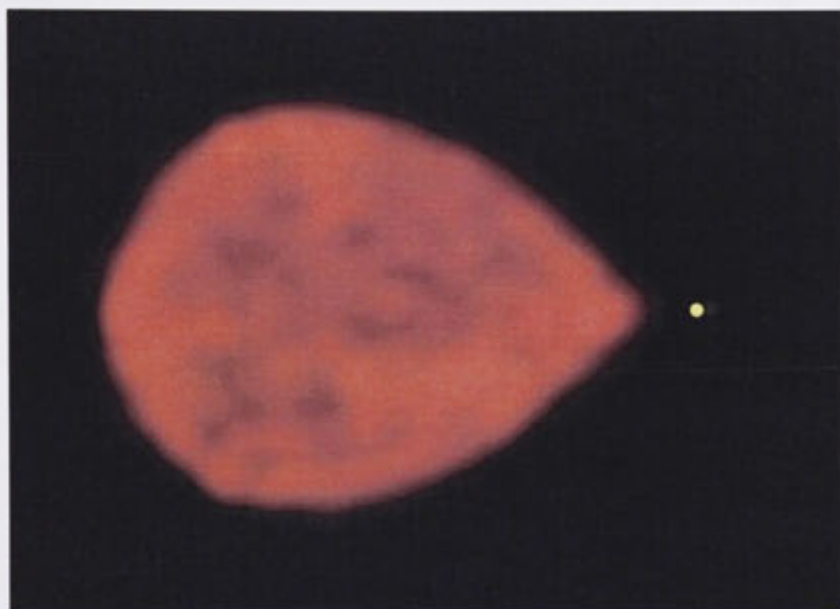
### 1.2.3 Ellipsoidal Variables

Ellipsoidal variables are close binaries in which one star is distorted by the gravitational influence of the other. When the primary evolves and begins to fill its Roche Lobe, it takes on an ellipsoidal or pear-like shape (a Roche Lobe equipotential). It may look something like the cartoon shown in Fig. 1.3. It is the distorted shape of the red giant which causes the light variations. In this way, the only determinant for ellipsoidal variation amplitude is the ratio of stellar radius to orbital separation, or the fractional filling of the Roche Lobe. Therefore as stars evolve up the giant branch and become larger, the fractional filling of their Roche Lobes increases, leading to detectable ellipsoidal light variations. Hence, stars in wider orbits become ellipsoidal variables during later stages of evolution than do stars in close orbits. Once detectable as an ellipsoidal variable, and continuing to evolve up the giant branch, the amplitude of the red giant's variability depends mostly on the fractional filling of the Roche Lobe, with small contributions from gravity darkening and limb darkening.

This aspherical shape leaves a clear fingerprint on the observable variations. Although the radial velocity curve of such a system will be dominated by the orbital motion, photometric variations will be produced by the changing orientation of the ellipsoid as it orbits its companion. To the observer, the apparent surface area of the star, and therefore its measured flux, changes as they see first a broad side of the ellipsoid, followed by a narrower end, and so on as the star rotates. This means that for every orbit, we see two light maxima – corresponding to the two ‘sides’ of the ellipsoid facing us — and two light minima — the two ‘ends’ facing us. Ellipsoidal variables can be readily identified from this fingerprint: two light cycles for every cycle of radial velocity.

As a class, ellipsoidal variables are relatively poorly studied. The first review was published by Morris (1985), who presented a catalogue of ellipsoids known at the time, showing they covered many spectral types. Their sample consisted mostly of short period systems. Beech (1986) noted that ellipsoidal variables were known at many different stages of evolution, occurring on the main sequence, in cataclysmic





**Figure 1.3:** A cartoon representation of an ellipsoidal red giant binary. In most cases the distortion of the red giant is less pronounced than the exaggerated shape shown here. Figure provided by P. Wood.

systems, and at many stages in between. All known ellipsoidal systems were circular or had low eccentricities, with Beech’s sample showing a mean eccentricity of 0.05. Hall (1990) studied 13 ellipsoidal variables with longer periods, in which the primaries were mostly early K giants. They noted the common presence of minima of unequal depths in ellipsoidal light curves, and suggested it was caused by increased limb darkening and gravity darkening on the ‘pointed end’ of the giant.

Wood et al. (1999) classified sequence E stars as contact binaries lying mostly on the RGB. Soszyński et al. (2004b) suggested they were more likely ellipsoidal variables, not yet overflowing their Roche Lobes, due to the presence of minima of unequal depths in many sequence E light curves. Soszyński et al. (2004b) also discovered some sequence E stars have eclipses superimposed on their ellipsoidal variations, while another subset showed light curves of curious shapes which they suggested were the result of eccentric orbits.

Neither Wood et al. (1999) nor Soszyński et al. (2004b) had radial velocity curves for sequence E stars, so no confirmation was available that stars on sequence E were in fact ellipsoidal variables. Adams et al. (2006) presented preliminary velocity curves for three of the sequence E stars presented in Chapter 4, in which doubling of the light curve with respect to the velocity curve was discernible. They repeated the assertion of Wood et al. (1999), that sequence E appeared to be populated by red giant binaries filling their Roche Lobes. At the time of the commencement of this thesis project, there was no unambiguous evidence that sequence E stars were ellipsoidal variables.

Wood et al. (1999) noted that sequence E light curves were regular, symmetric, and displayed lower amplitude than the pulsating variables, similar to the light curves of semidetached and contact binaries. Soszyński et al. (2004b)'s sequence E stars had orbital periods between 15 and 600 days, and when plotted at this period (twice the light variability period), they showed that sequence E appears as a lower luminosity continuation of sequence D.

Sequence E stars are not as numerous as LSPVs. Wood et al. (1999) found 0.5% of stars on the brightest magnitude of the LMC red giant branch lay on sequence E, with light amplitudes of  $\Delta M_R > 0.05$  mag. Soszyński et al. (2004b)'s larger sample has  $\sim 1.5\%$  of stars on the brightest magnitude of the LMC red giant branch classified as sequence E, with amplitudes of  $\Delta I > 0.025$  mag.

The curiously shaped variations that Soszyński et al. (2004b) found in  $\sim 10\%$  of their sequence E sample, and attributed to eccentric orbits, are of particular interest. They showed that simple light curve models supported this conjecture, despite the fact that according to tidal theory, circularisation should have occurred for these stars (Zahn, 1977; Verbunt & Phinney, 1995). Soszyński et al. (2004b) speculated that eccentricity may have been increased since orbital circularisation, by a mechanism such as mass transfer or interaction with a third companion.

Eccentric orbits are observed in many other classes of evolved binaries, where theory predicts that tidal circularisation should have occurred (van Winckel, 2003; Famaey et al., 2009; Izzard et al., 2010). The cause of these surprising eccentricities is unknown. Several mechanisms have been suggested that may increase eccentricity or maintain it despite tidal friction, such as mass transfer at periastron (Soker, 2000) and interaction with a circumbinary disk (Artymowicz et al., 1991). As yet this is an unsolved problem.

### 1.3 Aim of this Study

In this study we analyse the two classes of unusual LPVs described above, LSPVs on sequence D, and sequence E binaries. We aim to clarify the properties of LSPVs and constrain the possible mechanisms for their cause, using a more complete dataset than has previously been examined. We also aim to confirm whether sequence E stars are indeed ellipsoidal variables, and to describe the parameters of those in both circular and eccentric orbits.

These two classes of variables are collected here for a number of reasons. They both lie in the same region of the LPV period–luminosity diagram, they both affect AGB stars (although many sequence E variables are RGB stars), and in a figurative sense, they are both to some extent obscured by the clouds of mystery. Some sequence E stars show pulsations in their light curves, as LSPVs do. In addition, the sequence E stars are known binaries, and more than one model for LSP origin involves binary companions. Whether there is any true link between these classes remains to be seen.

## 1.4 Outline of Papers to be Presented

This thesis comprises a number of papers (either published or in preparation) describing LSPVs and sequence E stars. Each contains its own Abstract, Introduction, Conclusion and Reference list. Chapters 2, 4, and 5 were written for publication in the British journal ‘Monthly Notices of the Royal Astronomical Society’ and use British English, while Chapter 3, written for the American journal ‘The Astrophysical Journal’, uses American spelling.

Chapter 2 describes the analysis of a sample of LSPVs using both light and velocity curves. Particular attention is paid to the models of binarity and radial pulsation as possible causes for the LSP.

Chapter 3 contains a specific study into the nature of the mid-infrared excess shown by LSPVs, and how it differs from that of variables without LSPs.

Chapter 4 presents the first categorical evidence that sequence E stars are ellipsoidal variables, and uses radial velocity data to demonstrate that significant differences exist between LSPVs and sequence E stars.

Chapter 5 describes a study, using both light and velocity curves, of a subset of the sequence E ellipsoidal variables that have eccentric orbits. Absolute solutions, giving orbital parameters and component masses, are obtained via modelling with the Wilson–Devinney code.

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# Long Secondary Periods in Variable Red Giants

C. P. Nicholls, P. R. Wood, M.-R. L. Cioni and I. Soszyński, 2009, MNRAS 399, 2063

## Abstract

We present a study of a sample of LMC red giants exhibiting Long Secondary Periods (LSPs). We use radial velocities obtained from VLT spectral observations and MACHO and OGLE light curves to examine properties of the stars and to evaluate models for the cause of LSPs. This sample is much larger than the combined previous studies of Hinkle et al. (2002) and Wood, Olivier & Kawaler (2004).

Binary and pulsation models have enjoyed much support in recent years. Assuming stellar pulsation, we calculate from the velocity curves that the typical fractional radius change over an LSP cycle is greater than 30%. This should lead to large changes in  $T_{\text{eff}}$  that are not observed. Also, the small light amplitude of these stars seems inconsistent with the radius amplitude. We conclude that pulsation is not a likely explanation for the LSPs. The main alternative, physical movement of the star – binary motion – also has severe problems. If the velocity variations are due to binary motion, the distribution of the angle of periastron in our large sample of stars has a probability of  $1.4 \times 10^{-3}$  that it comes from randomly aligned binary orbits. In addition, we calculate a typical companion mass of  $0.09 M_{\odot}$ . Less than 1% of low mass main sequence stars have companions near this mass ( $0.06$  to  $0.12 M_{\odot}$ ) whereas  $\sim 25$  to 50% of low mass red giants end up with LSPs. We are unable to find a suitable model for the LSPs and conclude by listing their known properties.

## 2.1 Introduction

A subset of Long Period Variable stars (LPVs) were found several decades ago to show a secondary period of variation, in addition to their primary pulsation (e.g. Houk, 1963; Payne-Gaposchkin, 1954). These Long Secondary Periods, or LSPs, exceed the primary period in length by approximately one order of magnitude, a fact more recently confirmed by Wood et al. (1999). Wood et al. showed that

LPVs fall on four distinct period-luminosity sequences A–D, and they found an additional sequence, E, of red giant binaries. These multiple sequences have been confirmed in subsequent studies, and a splitting of sequence B into two sequences has since been discovered (Ita et al., 2004; Soszyński et al., 2004a; Fraser et al., 2005; Soszyński et al., 2007). Long Secondary Periods occupy sequence D, the sequence corresponding to variations with the longest period. The primary pulsation of these stars is usually found on sequence B (Wood et al., 1999).

Approximately 25–50% of Long Period Variables show an LSP (Wood et al., 1999; Soszyński et al., 2004b; Percy et al., 2004; Soszyński et al., 2007; Fraser et al., 2008). At present, there is no accepted explanation for LSPs. Wood et al. (1999) initially proposed a model wherein the sequence D stars are semidetached red giant binaries, as the length of their periods are consistent with those expected for binary systems with solar mass components. Several other models have been proposed to explain LSPs, including radial and nonradial pulsation, and dust effects. However, Wood et al. (2004) demonstrate that there are problems with all of these models. It is clear that further investigation is required in order to discover the cause of LSPs.

Here, we study a sample of sequence D stars in the Large Magellanic Cloud (LMC) in order to provide new constraints on models for the sequence D phenomenon. In particular, we present new spectra taken with the ESO's Very Large Telescope (VLT). We derive velocity curves, radii, and effective temperatures from these spectra and compare them in phase with light curves and associated quantities from the MACHO and OGLE databases.

Our study follows the methods of Hinkle et al. (2002) and Wood et al. (2004), who also compared both light and radial velocity data for sequence D stars. However we use a larger dataset and have the advantage of high quality and simultaneous light and velocity data, which we hope will give a more complete and accurate picture of the behaviour of LSP variables. Since our sample comes from the LMC, we also have the advantage that the distances, and hence derived luminosities, are well-determined.

## 2.2 Observations and Data Reduction

We chose a region of high star density in the middle of the LMC bar for this study, in order to get a large sample of sequence D stars in the 20 arcmin field of the FLAMES multifibre system on the VLT. The field centre is at  $05^h28^m15^s - 69^\circ45'43''$  J2000. It contained a sample of 58 variable red giants exhibiting LSPs which were obtained from the MACHO Project database. The MACHO Project was a photometric monitoring program undertaken between June 1992 and January 2000 at the 50-inch telescope at Mount Stromlo Observatory, Canberra. It was important to have simultaneous light and velocity data. Fortunately, OGLE light curves were taken at the times of our VLT observations. We have used both OGLE II and OGLE III I-band light curves in this study.

Spectra were obtained on 21 nights from 2003 November to 2006 March. The FLAMES/ GIRAFFE spectrograph (Pasquini et al., 2002) with a grating setting of

HR16 was used, giving spectra with a resolution of 23900 and a spectral interval of 6937–7250 Å. This region includes the TiO bandhead at 7050 Å, which can be used for spectral typing and to examine variation of  $T_{\text{eff}}$ , as well as for derivation of radial velocities. An exposure time of 20 minutes was used for all spectra. The spectra were obtained in service mode. Unfortunately no observations were taken between May and August when the Large Magellanic Cloud ( $RA = 05^h23'$ ) was only observable near twilight, leaving a long Winter gap in 2004 and 2005.

The raw spectra of the 58 sequence D stars, most of which have 21 observations from different dates, were reduced using the FLAMES/GIRAFFE pipeline, or the Swiss reduction pipeline. A number of sample spectra are shown in Figure 2.1, where the TiO bandhead is clearly visible in the second and third panels. The majority of the program stars have spectra similar to those shown in the top three panels, i.e., they are oxygen-rich giants of spectral types M and K. However, the sample does contain a number of carbon-rich stars (C-stars), as shown in the fourth panel of Figure 2.1.

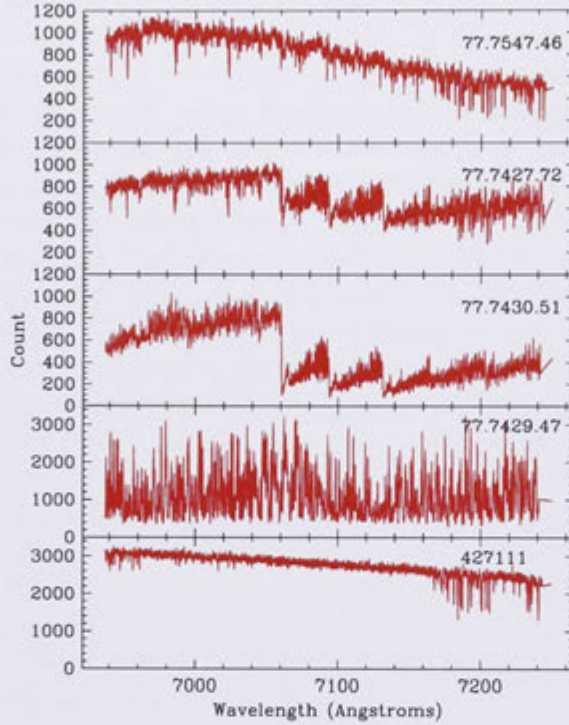
Using the IRAF software, each spectrum was visually examined and any obvious cosmic rays removed. There was a small percentage of bad data: in particular, spectra taken on two dates (2005 March 17 and 2005 September 10) had very few counts. This was due to the weather and seeing conditions at the time, and the spectra taken on these dates were discarded, leaving 19 good observations for most stars (some stars had fewer spectra due to the fibre allocation process in FLAMES). A small number of other spectra were discarded due to a low number of counts. These spectra did not fall on particular dates or particular target stars, and were distributed randomly throughout the dataset. Presumably, the low counts were due to the fibres for these stars being misaligned.

Relative heliocentric radial velocities were obtained through cross-correlation with the IRAF task *fxcor*. From each star, we visually selected a spectrum with a high number of counts and unbroadened lines, and this acted as the template spectrum for the star's cross-correlation (at certain phases lines are sometimes broadened due to unknown intrinsic processes). The cross-correlation was performed in the wavelength region 6950–7160 Å, as this region is relatively free of telluric lines, as can be seen in the lower panel of Figure 2.1. Errors in the radial velocities were also taken from *fxcor*. The mean velocity error of the sample is  $0.42 \text{ km s}^{-1}$ , and errors typically range between  $0.1$  and  $0.6 \text{ km s}^{-1}$ .

Because of uncertainty about the accuracy of the velocity calibration resulting from the pipeline reduction, the spectra were checked to see if any zero-point correction to the velocity was needed, before we calculated their absolute velocities. This procedure is now described.

### 2.2.1 Testing the Relative Telluric Radial Velocities

To check the velocity calibration, program stars were cross-correlated with a B star whose spectrum contained only telluric lines. Cross-correlation of a program spectrum to a telluric spectrum produces the relative telluric velocity of the two spectra, which should be zero if there are no calibration errors. This cross-correlation



**Figure 2.1:** Sample spectra from the VLT. *Top panel:* The spectrum of an O-rich program star with no TiO bands. *Second panel:* A program star with weak TiO bands. *Third panel:* A program star with strong TiO bands. *Fourth panel:* A C-rich program star. *Bottom panel:* A telluric star. Program stars are identified by their MACHO numbers. Note the different scale of the y-axis in the lower two panels.

was performed in the wavelength region 7160–7220 Å, as it has a large concentration of telluric lines (see Figure 2.1).

For most dates of observation, the relative telluric radial velocities were found to be not significantly different from zero, and so no systematic correction was applied to the spectra for those nights. However observations from two nights, with Heliocentric Julian Dates (HJD) of 2453377 and 2453643, consistently showed a positive velocity offset from zero, so a zero-point correction for the velocities on these dates was included for all stars. The velocity corrections for these dates were  $-2.061 \text{ km s}^{-1}$  and  $-0.729 \text{ km s}^{-1}$  respectively.

### 2.2.2 The Effect of Telluric Lines on Relative Radial Velocities

The highest concentration of telluric lines was found in the wavelength region 7160–7220 Å, but there were a small number in the program object region (6950–7160 Å, see Figure 2.1). There was a possibility that these lines would affect the calculated radial velocities, so this was examined. The telluric lines in the program object region of several program stars were removed using IRAF’s *telluric* command. Then the program spectra with telluric lines removed were cross-correlated against each other in the same way the original program spectra were. It was found that removing the telluric lines in this region had no significant effect on the velocities or errors, so telluric line removal was not performed.

### 2.2.3 Calculating the Absolute Radial Velocity

Following the zero-point corrections, the absolute radial velocities of the program stars were calculated. First, the template of each program star was cross-correlated to a star of known radial velocity, giving the absolute radial velocity of each template. Then by adding a keyword ‘*vhelio*’ (which contained the absolute radial velocity) to the image header of the template, we could cross-correlate the spectra for each star with its template to obtain the absolute radial velocities.

For the O-rich program stars, the radial velocity reference used was  $\alpha$  Cet. Its spectrum was taken using the echelle spectrograph (resolution 70000) on the late 74-inch telescope at Mount Stromlo Observatory, Canberra, Australia. For the C-stars, the reference used was the C-star X Vel, for which a spectrum was also taken with the 74-inch. The radial velocity used for  $\alpha$  Cet was  $-25.8 \text{ km s}^{-1}$  (taken from the 2006 Astronomical Almanac). The velocity for the spectrum of X Vel ( $-5.4 \text{ km s}^{-1}$ ) was obtained by cross-correlation with  $\alpha$  Cet (even though the spectral types are different, there was a strong cross-correlation peak due to common metal lines).

Radial velocities as a function of heliocentric Julian date (HJD) for a sample of the sequence D stars are shown in Table 2.1. Stars are identified by their MACHO numbers. Dashes denote dates for which there is no spectrum. The full table can be viewed in the online version of this paper, or in Appendix B.

### 2.2.4 Correcting for the Short-Period Variation

Because sequence D stars show two distinct modes of variability, it is necessary to correct the light and velocity data for the behaviour of the short (primary) period in order to accurately study the LSP. We need simultaneous velocity and light data for this purpose, so we use the OGLE *I* light curve in these procedures, even though it is missing the Southern Winter season.

First the OGLE *I* light curve was boxcar-smoothed over a time interval equal to the (primary) pulsation period. This removed the pulsation from the light curve. Once the smoothed LSP-only light curve was made, it was subtracted from the original light curve, leaving only the variations due to pulsation, *di*, or the ‘pulsation



**Table 2.1:** Heliocentric Radial Velocities of Sequence D Stars ( $\text{km s}^{-1}$ )

| HJD     | 77.7427.41 | 77.7427.72 | 77.7428.120 | 77.7428.65 | 77.7429.100 | 77.7429.47 | 77.7429.64 | 77.7430.46 | 77.7430.51 |
|---------|------------|------------|-------------|------------|-------------|------------|------------|------------|------------|
| 2954.85 | 240.85     | 273.53     | 273.61      | 297.74     | 314.55      | 280.43     | 278.15     | 244.02     | 266.31     |
| 3005.86 | 239.86     | 274.41     | 272.44      | 299.37     | 313.72      | 280.73     | 277.68     | 245.33     | 265.78     |
| 3067.60 | 241.32     | 275.08     | 272.69      | 298.12     | 313.20      | 279.58     | 277.01     | 244.83     | 267.10     |
| 3091.56 | 239.64     | 271.16     | 271.76      | 298.36     | 314.18      | 279.08     | 276.49     | 244.71     | 266.76     |
| 3280.86 | 241.59     | 273.70     | 272.70      | 295.91     | 314.24      | 278.73     | -          | 241.53     | 264.68     |
| 3324.76 | 239.26     | 275.30     | 273.26      | 294.60     | 314.51      | 278.14     | -          | 240.90     | 263.61     |
| 3344.80 | 240.04     | 274.01     | 273.34      | 295.59     | 315.15      | 277.93     | -          | 242.23     | 263.88     |
| 3376.58 | 239.38     | 274.15     | 272.60      | 295.73     | 314.17      | 277.91     | -          | 243.88     | 263.67     |
| 3418.69 | 238.11     | 273.68     | 272.59      | 296.53     | 315.73      | 277.24     | -          | 244.06     | 265.99     |
| 3471.51 | 237.08     | 271.80     | 272.23      | 298.19     | 314.98      | 278.01     | -          | 243.95     | 266.41     |
| 3623.88 | -          | -          | -           | -          | -           | -          | -          | -          | -          |
| 3642.83 | 240.15     | 271.86     | 273.68      | 297.61     | 313.64      | 281.31     | -          | 242.22     | 267.86     |
| 3644.82 | 239.89     | 271.50     | 273.67      | 297.36     | 313.43      | 281.03     | -          | 241.70     | 267.60     |
| 3663.86 | 240.49     | 271.74     | 273.28      | 296.62     | 312.03      | 281.83     | -          | 241.78     | 268.17     |
| 3664.86 | 240.62     | 271.92     | 273.53      | 296.83     | 311.85      | 281.99     | -          | 241.45     | 268.16     |
| 3685.67 | 240.85     | 273.02     | 272.99      | 297.64     | 313.59      | 282.93     | -          | 240.64     | 267.92     |
| 3709.79 | 240.50     | 269.51     | 273.40      | 297.15     | 314.57      | 284.06     | -          | 242.48     | 266.48     |
| 3741.60 | 242.04     | 272.47     | 272.40      | 296.61     | 313.84      | 282.54     | -          | 243.07     | 265.69     |
| 3768.62 | 241.31     | 273.48     | 274.19      | 297.47     | 313.53      | 280.68     | -          | 242.40     | 266.54     |
| 3819.50 | 242.35     | 274.62     | 273.97      | 296.13     | 313.88      | 282.12     | -          | 245.04     | 266.56     |



light curve’.

Similarly to obtaining the pulsation *light* curve, we obtained the pulsation *velocity* curve by making a binary fit (see Section 2.2.5) to the velocity data using the period of the LSP. The deviations of the velocity data,  $dv$ , from this fit form the pulsation velocity curve. We emphasise that although a binary fit was used for the purpose of obtaining a smooth fit, binarity may not be the physical mechanism behind the LSP.

For radial pulsation the light and velocity variations are shifted in phase relative to one another, so it is necessary to find the phase shift between the pulsation light and velocity curves in order to find the amplitude relation between the short-period light and velocity.

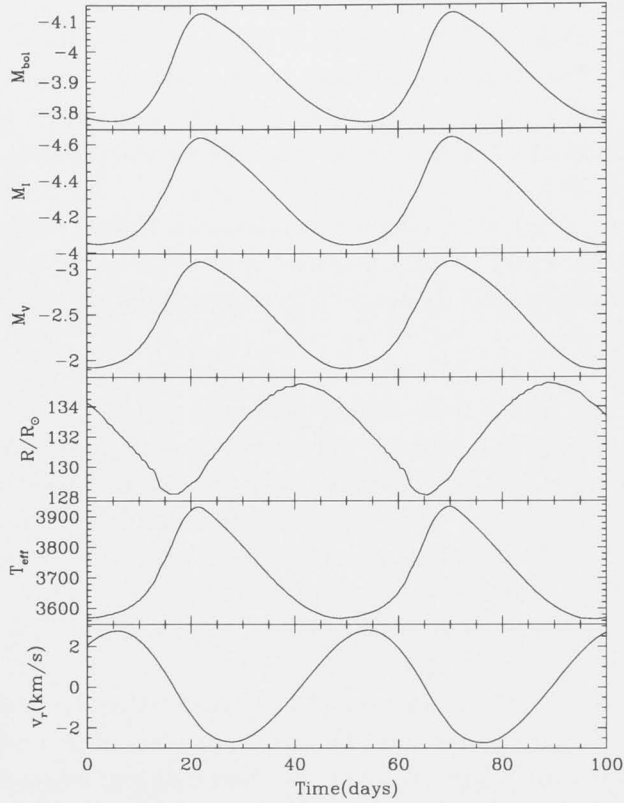
The phase correction was found by plotting the pulsation light versus pulsation velocity. By varying the phase shift of this plot, and judging by eye at which phase shift the pulsation light and velocity showed the clearest correlation, the best phase shift was found to be  $\sim 0.25$  of a cycle. This means that most often the  $I$  light minimum occurs close to the same phase as the mean rising radial velocity. Lebzelter, Kiss & Hinkle (2000) and Lebzelter & Hinkle (2002) find that the phase shift between the light and velocity variations of pulsating SRVs is 0.5. This means maximum radial velocity occurs at minimum light, and vice versa. The phase shift is discussed further below.

Next, the slope of the light–velocity amplitude correlation for pulsation was measured, to give the velocity correction. From examination of several stars with relatively large pulsation amplitudes, it was concluded that the velocity correction was  $\sim 15 \text{ km s}^{-1} \text{ mag}^{-1}$  in  $I$ . Generally, the correction to the LSP velocity resulting from these processes is small, less than  $0.6 \text{ km s}^{-1}$ , as the median value of  $di$  is  $\sim 0.04$  mag.

In order to further investigate the phase relation between the velocity and light curves, we constructed a model semi-regular pulsator using the nonlinear pulsation code described in Keller & Wood (2006). The model is a first overtone pulsator, appropriate for a sequence B variable. The model oscillations should be similar to the primary oscillation in the sequence D variables studied here, and the semi-regular variables studied by Lebzelter & Hinkle (2002). The model had  $M = 1.5 M_{\odot}$ ,  $L = 3000 L_{\odot}$ ,  $T_{\text{eff}} = 3740 \text{ K}$ , helium abundance  $Y = 0.3$  and metallicity  $Z = 0.004$ .  $M_V$  and  $M_I$  were computed from the M star model atmospheres of Houdashelt et al. (2000), assuming  $[Fe/H] = -0.5$ .

The model light and radial velocity curves are shown in Figure 2.2. The graph also shows the time variation of  $T_{\text{eff}}$  and radius for comparison with observational estimates of these quantities in later sections.

The model shows that minimum light occurs between mean increasing radial velocity (as estimated here) and maximum radial velocity (as estimated by Lebzelter & Hinkle, 2002). The model also predicts a ratio of velocity to  $I$  amplitude of  $9.2 \text{ km s}^{-1} \text{ mag}^{-1}$ , somewhat smaller than the estimate of  $15 \text{ km s}^{-1} \text{ mag}^{-1}$  given here. Given the small size of the corrections to velocity that we have applied, the uncertainty in the relative phase and amplitude ratio of velocity and  $I$  amplitude will not significantly affect the resulting velocity curve of the sequence D variability.

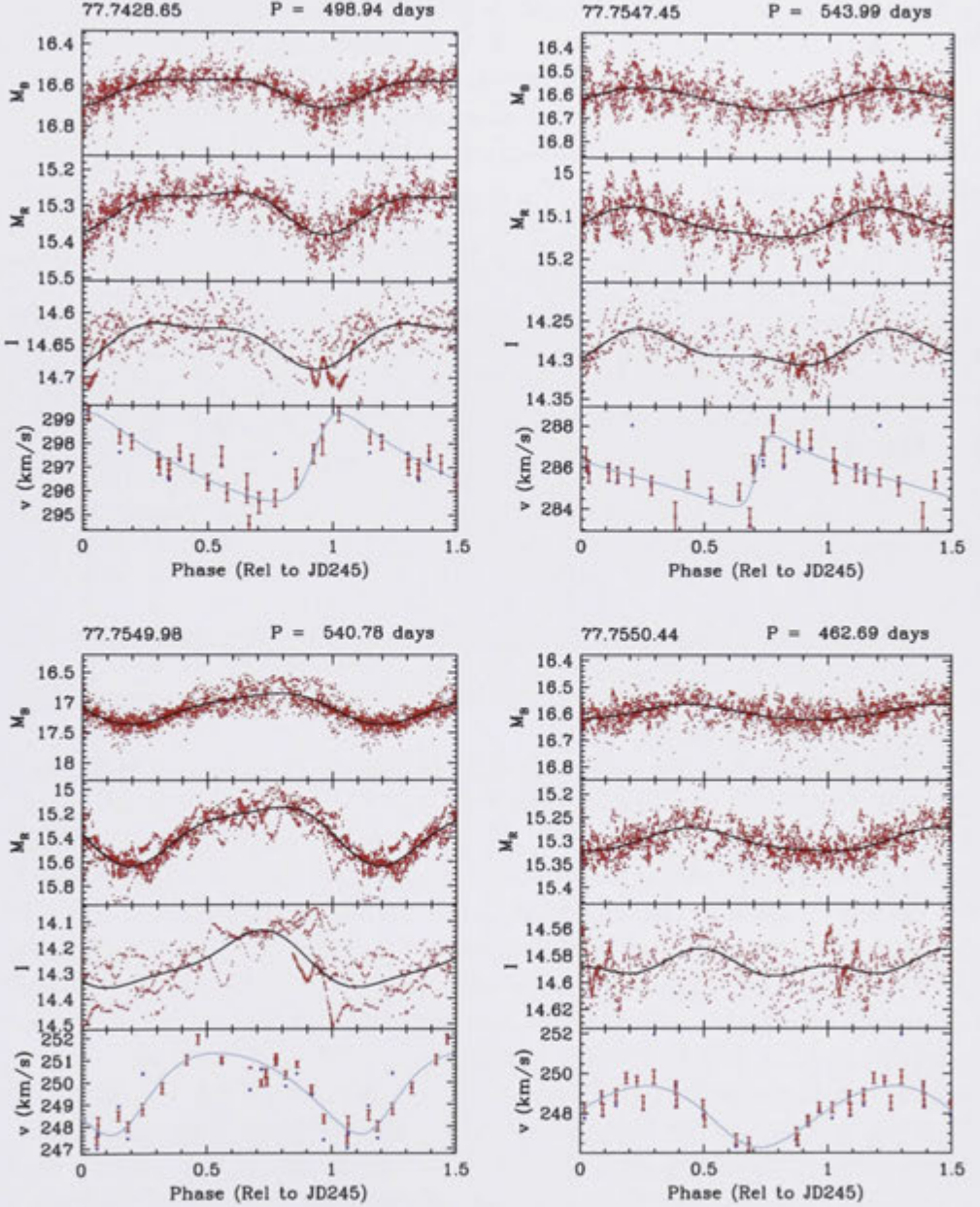


**Figure 2.2:**  $M_{bol}$ ,  $M_I$ ,  $M_V$ ,  $R/R_{\odot}$ ,  $T_{eff}$  and  $v_r$  plotted against time in a model red giant variable pulsating in the first overtone mode. The radius  $R$  is defined at optical depth  $\frac{2}{3}$  and  $v_r$  is the radial velocity seen by a distant observer. It is defined as  $-v/1.4$ , where  $v$  is the pulsation velocity, relative to the centre of the star, of matter near optical depth  $\frac{2}{3}$ . The factor 1.4 is the correction factor from observed to pulsation velocities for red giant pulsators (Scholz & Wood, 2000).

### 2.2.5 Obtaining LSP Parameters and Narrowing the Sample

Following the corrections described above, we were now in a position to analyse the light and velocity variations associated with the Long Secondary Period. A binary fit was made to the corrected velocity data of the LSP using a Fortran program, FITALL, to obtain the parameters of the velocity curve. FITALL also made a Fourier series fit (with a frequency  $f$  and one harmonic  $2f$ ) to the MACHO  $M_B$ ,  $M_R$  and OGLE  $I$  light curves, and to  $(M_B - M_R)$ . Some examples of the fits to the light and velocity data made by FITALL can be seen in Figure 2.3.

Due to the poor quality of the data for some stars, the original sample of 58 sequence D stars had to be reduced. Some stars had large velocity errors due to poor-quality or few spectra, or no OGLE light curve, so they were excluded from the sample. A few stars had LSPs near 365 days leading to a large unfilled gap in



**Figure 2.3:** Light and velocity curves plotted against phase for four sequence D stars. The blue velocity points without error bars are the radial velocities without corrections and the red points with error bars are the radial velocities that have been corrected for pulsation and had specific date corrections. Also shown are the Fourier fits to the light data (black lines), and the Binary fits to the velocity data (cyan lines), both made by FITALL. Plots for the entire sample can be found in Appendix C.

the velocity curve, and could not be analysed.

Next, for each of the remaining stars we judged by eye the quality of each star's binary fit, and eliminated all stars judged to have poor fits to their velocity data. Finally, we were left with a reduced sample of 30 sequence D stars, from the original 58. The parameters of the velocity fit for these 30 stars are shown in Table 2.2, where  $\gamma$  is the system velocity,  $K$  is the velocity semi-amplitude,  $e$  is the eccentricity,  $\omega$  is the angle of periastron,  $T$  is the date of periastron,  $P$  is the period, and  $f(m)$  is the mass function, given by

$$f(m) = \frac{K^3 P}{2\pi G} = \frac{m^3 \sin^3 i}{(m + M)^2} \quad (2.1)$$

in which  $M$  is the mass of the star, and  $m$  the mass of its companion.

## 2.3 Results

In this Section, we discuss some general results that are not model specific. Model specific results are presented in Section 2.4.

### 2.3.1 The True Distribution of the Velocity Amplitude

The distribution of velocity amplitude is an important parameter for most models of the sequence D phenomenon.

A histogram of the velocity amplitudes of our sample is shown in Figure 2.4, with the values separated into bins of width  $0.5 \text{ km s}^{-1}$ . It is important to note that we use the full or peak-to-peak amplitude, as opposed to the semi-amplitude. These amplitudes are obtained from the binary orbit fits to the observed velocities. We find that the velocity amplitude is concentrated mainly between  $2.5$  and  $5.0 \text{ km s}^{-1}$ , with the highest number of stars falling in the bin centred at  $3.5 \text{ km s}^{-1}$ . The distribution has a median value of  $3.53 \text{ km s}^{-1}$ . Thus our sequence D stars all have low, relatively similar velocity amplitudes. These results are consistent with the results of Hinkle et al. (2002)'s and Wood et al. (2004)'s analysis of Galactic LSP variables.

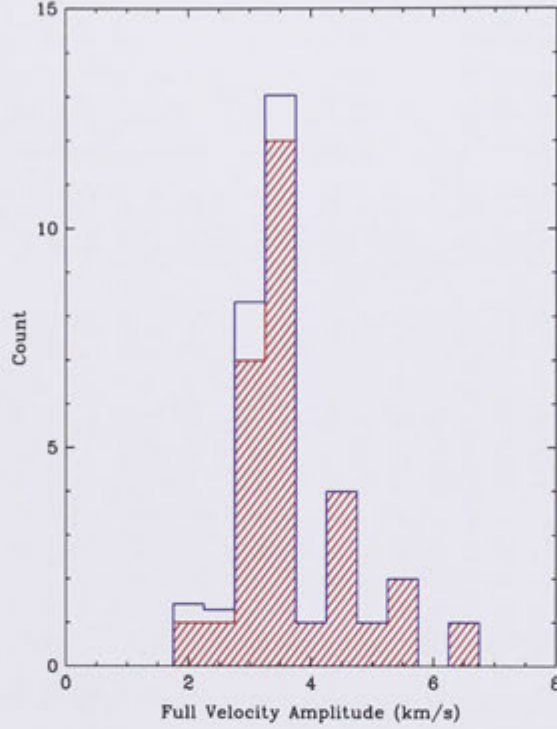
There are very few stars in our sample with velocity amplitudes  $< 3.0 \text{ km s}^{-1}$ . To find out if we could detect such stars we performed a Monte Carlo simulation. Fifty stars were simulated for each of the velocity amplitudes of  $3.0$ ,  $2.0$ ,  $1.0$  and  $0.5 \text{ km s}^{-1}$ . The period, eccentricity, and time of periastron were all selected randomly. The number of velocity points in each simulation was the same as the number of observations (19) and they were distributed in time identically to the observations. Random noise was added to each point, drawn from a normal distribution whose mean was the mean velocity error in the observations. In plots for visual examination, an errorbar was added for each point, drawn from a uniform distribution between  $0.2$  and  $0.5 \text{ km s}^{-1}$  (consistent with observed errors).

A binary fit was made to the simulated velocities in the same way as to the observed velocities (see Section 2.2.5). The simulated data were put through the same reduction steps as the observed data, to see what percentage would pass.

Table 2.2: Orbital Elements

| Star         | $\gamma$<br>(km s <sup>-1</sup> ) | K<br>(km s <sup>-1</sup> ) | e             | $\omega$<br>(deg) | T<br>(HJD)      | P<br>(days) | f(m)<br>(10 <sup>-4</sup> M <sub>⊙</sub> ) | No.<br>obs. |
|--------------|-----------------------------------|----------------------------|---------------|-------------------|-----------------|-------------|--------------------------------------------|-------------|
| 77.7427.41   | 239.812 ± 0.144                   | 1.870 ± 0.175              | 0.436 ± 0.139 | 189.68 ± 6.91     | 3491.19 ± 13.82 | 776.18      | 3.835 ± 1.377                              | 19          |
| 77.7427.72   | 273.087 ± 0.186                   | 1.626 ± 0.271              | 0.547 ± 0.182 | 257.71 ± 6.59     | 3251.47 ± 10.27 | 488.67      | 1.277 ± 0.840                              | 19          |
| 77.7428.65   | 297.159 ± 0.116                   | 1.850 ± 0.095              | 0.402 ± 0.115 | 290.72 ± 4.53     | 3462.77 ± 4.97  | 498.94      | 2.512 ± 0.567                              | 19          |
| 77.7429.100  | 313.955 ± 0.145                   | 0.966 ± 0.188              | 0.187 ± 0.145 | 182.16 ± 12.49    | 3166.86 ± 16.46 | 473.24      | 0.419 ± 0.248                              | 19          |
| 77.7429.47   | 280.326 ± 0.108                   | 2.271 ± 0.120              | 0.475 ± 0.108 | 274.88 ± 3.59     | 3547.93 ± 9.50  | 1078.33     | 8.910 ± 2.264                              | 19          |
| 77.7430.46   | 243.159 ± 0.129                   | 1.687 ± 0.161              | 0.195 ± 0.127 | 279.99 ± 5.57     | 3370.88 ± 6.56  | 416.45      | 1.957 ± 0.579                              | 19          |
| 77.7430.51   | 266.274 ± 0.212                   | 2.203 ± 0.137              | 0.583 ± 0.202 | 227.13 ± 3.50     | 4148.37 ± 11.12 | 798.34      | 4.737 ± 2.686                              | 18          |
| 77.7547.44   | 271.204 ± 0.148                   | 2.150 ± 0.163              | 0.151 ± 0.147 | 87.27 ± 4.59      | 3314.19 ± 10.26 | 870.06      | 8.654 ± 2.053                              | 19          |
| 77.7547.45   | 285.675 ± 0.142                   | 1.697 ± 0.181              | 0.590 ± 0.141 | 278.00 ± 3.93     | 3106.62 ± 6.16  | 543.99      | 1.450 ± 0.725                              | 19          |
| 77.7549.42   | 263.993 ± 0.146                   | 1.758 ± 0.235              | 0.274 ± 0.144 | 225.45 ± 3.01     | 3668.10 ± 7.03  | 868.76      | 4.351 ± 1.832                              | 18          |
| 77.7549.46   | 263.453 ± 0.188                   | 1.542 ± 0.225              | 0.201 ± 0.186 | 242.52 ± 12.16    | 3169.49 ± 20.31 | 742.68      | 2.651 ± 1.201                              | 19          |
| 77.7549.98   | 249.842 ± 0.123                   | 1.848 ± 0.101              | 0.232 ± 0.123 | 210.85 ± 5.25     | 3336.64 ± 7.44  | 540.78      | 3.254 ± 0.609                              | 19          |
| 77.7550.43   | 244.373 ± 0.170                   | 1.743 ± 0.235              | 0.391 ± 0.169 | 255.86 ± 7.39     | 3371.03 ± 9.06  | 452.37      | 1.936 ± 0.906                              | 18          |
| 77.7550.44   | 247.976 ± 0.085                   | 1.536 ± 0.129              | 0.118 ± 0.085 | 146.30 ± 4.21     | 3540.15 ± 5.29  | 462.69      | 1.701 ± 0.432                              | 19          |
| 77.7552.111  | 273.144 ± 0.157                   | 1.800 ± 0.180              | 0.217 ± 0.156 | 169.75 ± 6.69     | 3433.09 ± 8.76  | 462.96      | 2.604 ± 0.828                              | 19          |
| 77.7667.918  | 260.681 ± 0.171                   | 2.846 ± 0.130              | 0.409 ± 0.166 | 192.60 ± 5.54     | 3182.52 ± 4.05  | 310.17      | 5.632 ± 1.576                              | 19          |
| 77.7669.1027 | 268.918 ± 0.202                   | 3.360 ± 0.174              | 0.351 ± 0.202 | 276.46 ± 5.69     | 3167.47 ± 3.76  | 266.77      | 8.608 ± 2.477                              | 19          |
| 77.7669.1028 | 220.264 ± 0.125                   | 1.574 ± 0.186              | 0.171 ± 0.125 | 182.39 ± 5.47     | 3220.97 ± 9.44  | 623.22      | 2.409 ± 0.868                              | 19          |
| 77.7669.973  | 273.015 ± 0.131                   | 2.378 ± 0.215              | 0.257 ± 0.125 | 328.59 ± 2.37     | 3193.90 ± 2.05  | 367.77      | 4.622 ± 1.340                              | 19          |
| 77.7669.991  | 302.589 ± 0.094                   | 1.271 ± 0.105              | 0.529 ± 0.090 | 191.96 ± 7.42     | 3091.45 ± 4.05  | 241.77      | 0.315 ± 0.100                              | 19          |
| 77.7671.282  | 239.954 ± 0.116                   | 1.398 ± 0.184              | 0.259 ± 0.114 | 47.28 ± 3.13      | 3624.34 ± 7.04  | 836.86      | 2.133 ± 0.866                              | 20          |
| 77.7672.38   | 253.020 ± 0.166                   | 2.103 ± 0.175              | 0.363 ± 0.166 | 258.54 ± 9.82     | 3200.71 ± 11.93 | 660.92      | 5.154 ± 1.676                              | 19          |
| 77.7673.25   | 252.165 ± 0.144                   | 2.764 ± 0.215              | 0.201 ± 0.143 | 217.94 ± 3.67     | 3248.27 ± 4.43  | 392.27      | 8.067 ± 2.019                              | 19          |
| 77.7910.59   | 319.326 ± 0.157                   | 1.729 ± 0.168              | 0.300 ± 0.156 | 282.05 ± 5.50     | 3181.29 ± 7.37  | 473.72      | 2.203 ± 0.725                              | 18          |
| 77.7912.33   | 322.424 ± 0.164                   | 1.480 ± 0.183              | 0.257 ± 0.162 | 247.00 ± 7.50     | 3111.40 ± 5.92  | 320.79      | 0.973 ± 0.383                              | 19          |
| 77.7912.36   | 300.304 ± 0.115                   | 1.548 ± 0.147              | 0.618 ± 0.112 | 255.40 ± 4.39     | 3145.92 ± 4.22  | 519.20      | 0.970 ± 0.428                              | 19          |
| 77.7912.66   | 264.590 ± 0.111                   | 1.458 ± 0.178              | 0.487 ± 0.110 | 55.66 ± 5.03      | 3136.40 ± 3.33  | 339.35      | 0.725 ± 0.307                              | 19          |
| 77.7914.39   | 237.481 ± 0.112                   | 1.760 ± 0.130              | 0.120 ± 0.112 | 246.58 ± 5.57     | 3421.15 ± 10.36 | 717.39      | 3.964 ± 0.895                              | 19          |
| 77.8034.380  | 238.063 ± 0.253                   | 2.140 ± 0.099              | 0.322 ± 0.229 | 207.27 ± 5.82     | 3265.28 ± 10.60 | 401.59      | 3.459 ± 0.981                              | 19          |
| 77.8035.48   | 302.518 ± 0.142                   | 1.853 ± 0.167              | 0.081 ± 0.141 | 110.90 ± 8.01     | 3186.59 ± 16.24 | 719.69      | 4.695 ± 1.281                              | 19          |





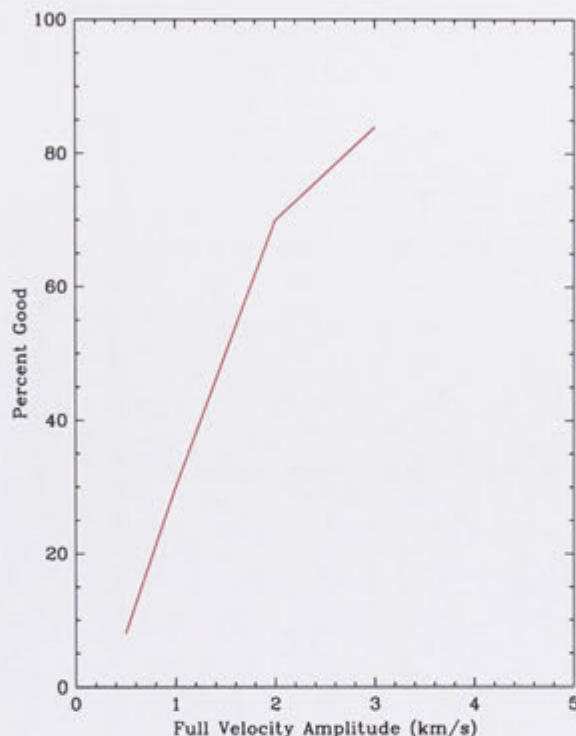
**Figure 2.4:** A histogram of the observed full velocity amplitude is plotted in red (forward shading). Note the clustering around  $3.5 \text{ km s}^{-1}$ . Overplotted in blue is the modified histogram to account for the observational detection probability calculated in our Monte Carlo simulation (see text for details).

The percentages can be seen in Figure 2.5. This tells us that we should be able to detect velocity amplitudes  $< 3.0 \text{ km s}^{-1}$ . Using our simulated percentages, we can estimate the true number of stars at each velocity amplitude by dividing the observed histogram by the observable percentage. The resulting modified velocity amplitude histogram is shown overplotted on the observed histogram in Figure 2.4.

The fact that we do not observe many sequence D stars with velocity amplitudes  $< 3.0 \text{ km s}^{-1}$  suggests there are not many to be observed. We conclude that the true distribution of sequence D velocity amplitudes, represented in Figure 2.4, shows a strong peak near  $3.5 \text{ km s}^{-1}$ .

### 2.3.2 Correlation of Light and Velocity Amplitudes

Light amplitude is plotted against velocity amplitude in Figure 2.6. There is no obvious correlation between light and velocity amplitudes in either  $M_B$ ,  $M_R$ , or  $I$ . As noted previously the velocity amplitude has a small spread, and peaks at



**Figure 2.5:** Fraction of simulated velocity curves which pass our data reduction process, for different velocity amplitudes.

the small value of  $3.5 \text{ km s}^{-1}$ . In particular, stars with small light amplitudes have velocity amplitudes as large as those stars with the largest light amplitudes.

### 2.3.3 Correlation of Velocity Amplitude with Magnitude and Period

Velocity amplitude is plotted against  $K$  magnitude in Figure 2.7, which shows a suggestion that velocity amplitude increases slowly with luminosity. A similar correlation is seen in Figure 2.8 between velocity amplitude and LSP. However these possible correlations are disrupted by the presence of a few stars with larger velocity amplitudes, that fall apart from the general relation.

## 2.4 Testing and Constraining Models

Here we examine some of the more plausible and popular models of LSPs, in the light of our new data.

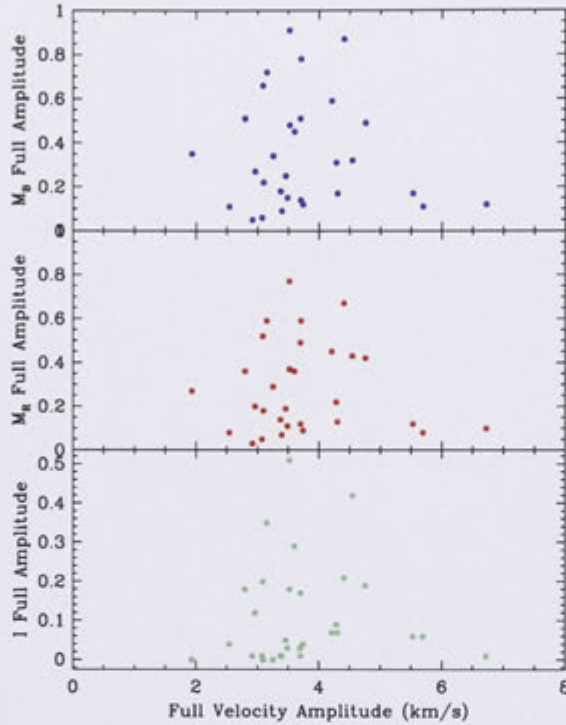


Figure 2.6: Light amplitude plotted against velocity amplitude for  $M_B$ ,  $M_R$ , and  $I$ .

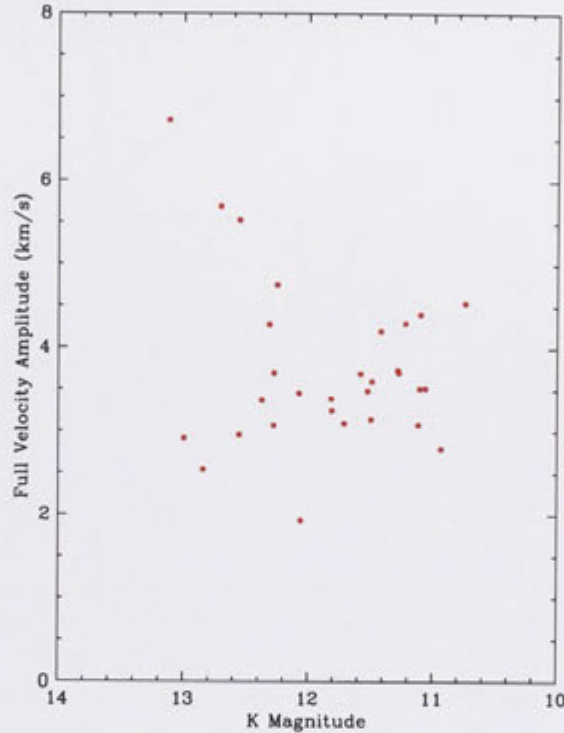
## 2.4.1 The Binary Model

The model of binary motion as an explanation for LSPs has been much debated since its proposal by Wood et al. (1999). In its favour, binary motion may be able to explain the sequence D velocity curves, and the light variation was originally thought by Wood et al. to resemble an eclipse of the star by a dusty cloud surrounding a small, orbiting companion. However when this model was further examined by Hinkle et al. (2002) and Wood et al. (2004), two main problems were found: the companion mass was calculated to be always  $\sim 0.1 M_\odot$ , and the characteristic shape of sequence D stars' velocity curves was shown to imply that the angle of periastron is not uniformly distributed between 0 and  $2\pi$ . With our larger sample we can place tighter constraints on these properties.

### 2.4.1.1 The Companion Mass

In a binary system, the velocity amplitude and period give an estimate of the mass of the companion. For a typical sequence D star with an LSP of 500 days, a typical velocity amplitude of  $3.5 \text{ km s}^{-1}$ , and an assumed total system mass of  $M = 1.5 M_\odot$ ,



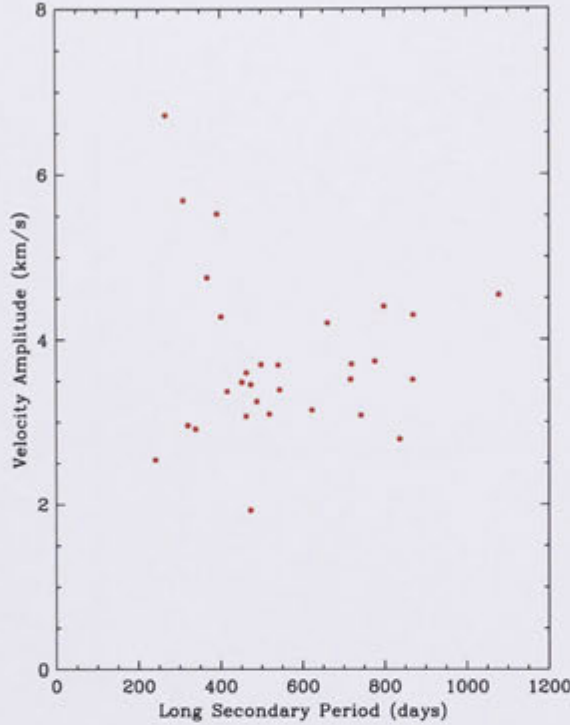


**Figure 2.7:** Velocity amplitude plotted against  $K$  magnitude.

the orbital separation is of the order of 1.4 AU and the companion has a mass of  $0.09 M_{\odot}$ . This means it is a very low mass main sequence star or a brown dwarf. There is an observed deficit of brown dwarf companions to main sequence stars, compared to both more massive stellar companions and less massive planetary companions. This is known as the ‘Brown Dwarf Desert’ (McCarthy & Zuckerman, 2004; Grether & Lineweaver, 2006). The range of likely companion masses can be found by calculating the companion mass for velocity amplitudes within one sigma of the mean of  $3.5 \text{ km s}^{-1}$ . We find a companion mass range of  $0.06$  to  $0.12 M_{\odot}$ . Using the fits to the data in Figure 8 of Grether & Lineweaver (2006), we find that only 0.86% of low mass main sequence stars have companions with masses in this range. Thus binarity is an unlikely model, when we remember that  $\sim 30\%$  of low mass stars will exhibit LSPs when they pass through the AGB stage.

#### 2.4.1.2 Correlation of Velocity Amplitude with Light Amplitude, Magnitude and Period

We would not expect the velocity and light amplitudes to be related in a binary model where the light variation is due to an eclipse phenomenon (by a cloud in the



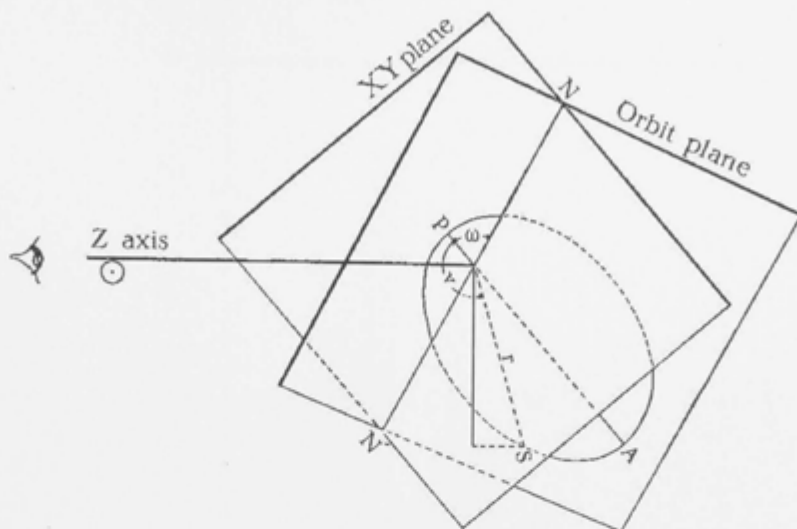
**Figure 2.8:** Velocity amplitude plotted against LSP.

Wood et al., 1999, model). However, these amplitudes may be related if the light variations were caused by distortion of the red giant by its unseen companion (see Section 2.4.1.5).

As noted in Section 2.3.3, only a hint of a correlation is seen between velocity amplitude and  $K$  magnitude (Figure 2.7), and with LSP (Figure 2.8). We cannot draw any conclusions from this in the context of a binary model.

#### 2.4.1.3 The Distribution of the Angle of Periastron

One of the most conclusive ways to test the plausibility of the binary model as a cause for the LSPs is to examine the distribution of the angle of periastron,  $\omega$ . The angle of periastron is a measure of the orientation of a binary's orbit, and is defined as the angle at which periastron (the closest approach of the two stars) occurs relative to the line of intersection of the orbital plane and the plane of the sky, measured in the direction of orbit. A visual representation is shown in Fig. 2.9. As Hinkle et al. (2002) and Wood et al. (2004) note, the observed distribution of  $\omega$  should be uniform over the whole range of angles, since one would expect binary orbits to be randomly aligned in space.

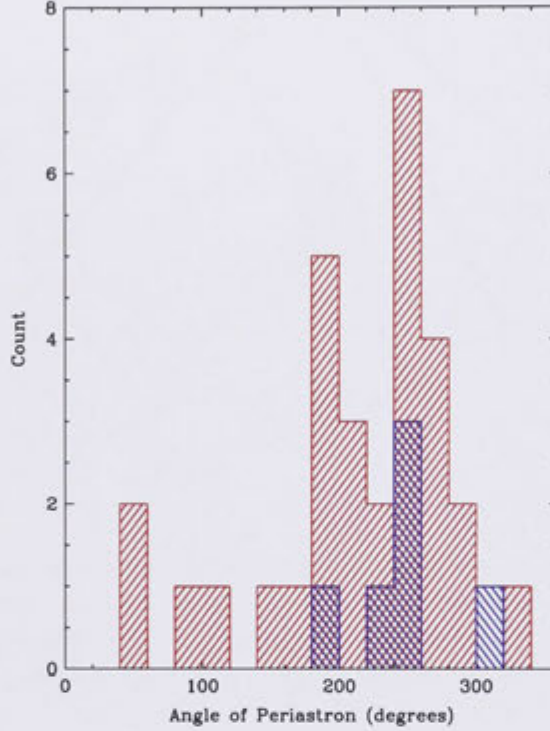


**Figure 2.9:** The definition of angle of periastron, reproduced from Aitken (1918). The plane XY is the plane of the sky, and the line NN' is the line of nodes, along which the sky and orbital planes intersect. Periastron occurs at point P. The angle of periastron,  $\omega$ , is defined to be zero at the point on the line of nodes where the star has positive radial velocity, i.e. is moving away from the observer.

The angle of periastron was calculated by the program FITALL as part of the binary fit made to our radial velocity data. The distribution of the angle of periastron is plotted as a histogram in Figure 2.10, with the data divided into bins  $20^\circ$  in width. Note that since the errors in the angle of periastron are typically around  $5^\circ$  (Table 2.2), the distribution of angle of periastron shown in Figure 2.10 will not be significantly broadened by these errors. There is a clear bias in the distribution towards angles  $> 180^\circ$ , and the median of the sample is  $227^\circ$ . The distribution of the angles of periastron calculated by Hinkle et al. (2002) and Wood et al. (2004) for their small samples of Galactic stars has been overplotted. It is clear that their values of  $\omega$  lie in the same region as the bulk of the present sample. This shows that the LSPs share a common cause, whether found in the LMC or in our own Galaxy.

Hinkle et al. (2002) and Wood et al. (2004) both found that the characteristic shape of the velocity curves suggests an eccentric orbit and a large angle of periastron, and that the distribution of the calculated angle of periastron was inconsistent with what would be expected if the sequence D stars were binaries, as no satisfactory explanation could be found for this bias towards higher angles. But given their small sample size, their conclusions were not highly significant. We can quantify and greatly improve these claims by using a Kolmogorov-Smirnov, or K-S Test, with our new data.

We have used the one-sample K-S Test, in the form of the Fortran 77 subroutine KSONE (provided in Press et al., 1986), to compare our distribution of the angle



**Figure 2.10:** The distribution of the angle of periastron,  $\omega$ . This study's sample is plotted in red (forward shading). The combined sample of Hinkle et al. (2002) and Wood et al. (2004) is shown in blue (back shading). Two stars have been dropped from Hinkle et al.'s sample and one from Wood et al.'s, due to overly large errors for  $\omega$ .

of periastron to the uniform distribution. We find that the probability that our distribution of  $\omega$  is consistent with the uniform distribution is  $1.4 \times 10^{-3}$ . In other words, the probability that the sequence D stars are binaries is extremely small. This is a major result from this study.

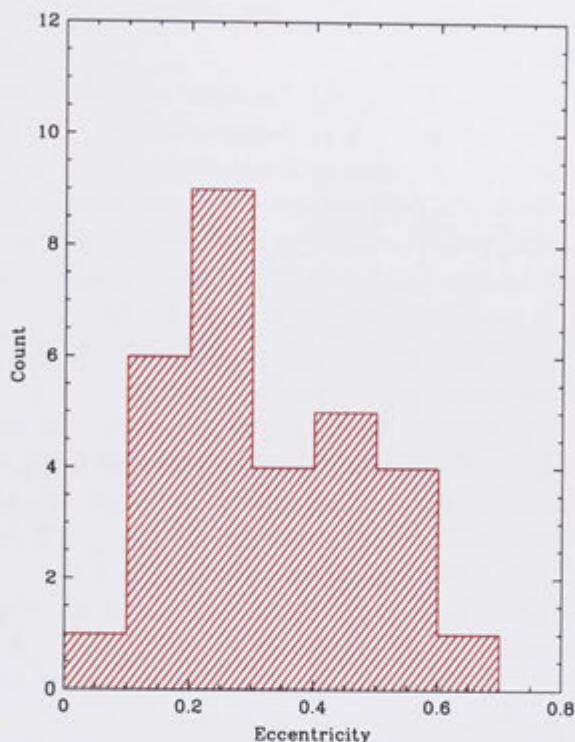
An angle of periastron between  $180^\circ$  and  $360^\circ$  means that at periastron, the red giant is closest to the observer, with the smaller companion further away. It is hard to see what selection effects could cause an LSP to be observed only in these binary orientations.

#### 2.4.1.4 The Distribution of the Eccentricity

A histogram showing the distribution of the eccentricity is shown in Figure 2.11. The eccentricity was calculated by FITALL as one of the orbital parameters of the binary fit to the velocity data.

The plot shows that if the sequence D stars are caused by binary motion, then





**Figure 2.11:** The distribution of the eccentricity.

they are in eccentric orbits. This confirms the suggestion of Hinkle et al. (2002) and Wood et al. (2004). The median eccentricity of the sample is 0.3.

#### 2.4.1.5 Ellipsoidal Variables

An ellipsoidal variable is a binary star which is tidally distorted by an orbiting companion into an ellipsoidal shape. Light variability is caused mostly by the variation of the apparent surface area of the star seen by the observer as the star rotates. Its velocity curve is dominated by orbital motion, with a small contribution from the rotation of the limb-darkened ellipsoid.

The light curve for an ellipsoidal variable is expected to have two maxima and minima per orbit, due to the star's shape. However, the velocity curve is expected to have only one maximum and minimum per orbit. We can use this characteristic to investigate the plausibility of ellipsoidal variability as an explanation for the LSP variation.

Soszyński et al. (2004b) show that the light curves of *sequence E* variables are satisfactorily explained by ellipsoidal variability. Their data show a partial overlap of sequences D and E in the P–L diagram, and so they suggest that the Long

Secondary Periods may have a binary ellipsoidal origin. Soszyński (2007) explores this possibility further by searching for ellipsoidal or eclipsing shapes in residual LSP light curves. He finds these variations in  $\sim 5\%$  of his sample, and adopts the binary model to explain LSPs.

However, with our new dataset (which includes some sequence E stars), the difference between sequence D and sequence E mechanisms can now be vividly demonstrated by the difference between the light and velocity curves of sequence D and E stars. The phased-up light and velocity curves of sequence E stars show that the light curve completes two full cycles to every single cycle of the radial velocity, as expected for an ellipsoidal variable (Adams et al., 2006, Nicholls, Wood & Cioni, in preparation). However, Figure 2.3 shows that sequence D stars do not display this behaviour: the phased-up light and velocity curves match each other cycle for cycle. Furthermore, sequence E stars typically have velocity amplitudes of  $30 \text{ km s}^{-1}$  or more while the sequence D stars have significantly lower typical amplitudes of  $3.5 \text{ km s}^{-1}$ . Soszyński (2007) predicted that sequence D stars showing residual ellipsoidal or eclipsing-type variations should have large velocity amplitudes, similar to those observed for sequence E stars. One of our stars (77.7671.282) was noted by Soszyński as a double-humped LSPV and its velocity amplitude is only  $\sim 4 \text{ km s}^{-1}$ . Additionally, none of our LSP sample show typical sequence E velocity amplitudes (see Figure 2.4). Sequence D and E variables clearly have distinctly different velocity amplitudes.

There is an unambiguous distinction between the mechanisms of variability responsible for causing sequences D and E. We can now state with some certainty that binary star ellipsoidal variability is not the cause of the LSP.

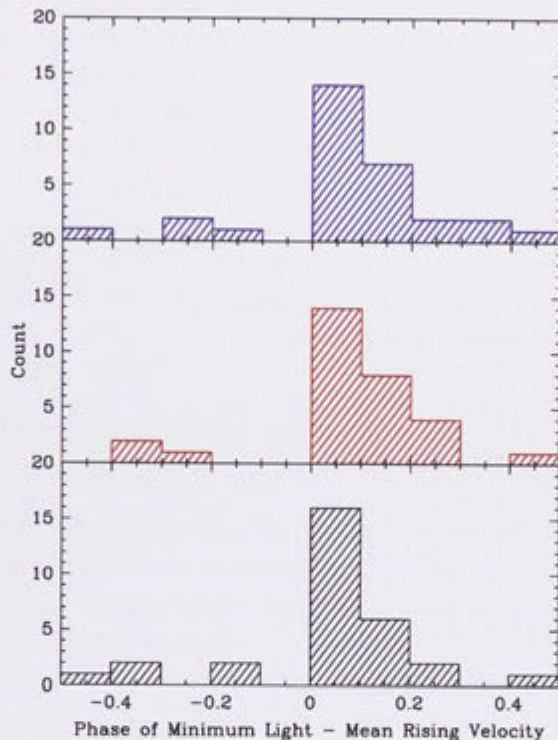
Similar to the sequence E ellipsoidal variables are symbiotic binaries, which are red giants with an accreting white dwarf companion, often in an eccentric orbit. Radial velocity amplitudes of these systems are usually  $\geq 8 \text{ km s}^{-1}$ , and the red giant may be a Mira variable (Hinkle et al., 2006). However, symbiotic spectra show high temperature emission lines from accretion onto the white dwarf, something that has not been seen in either the sequence E or sequence D spectra. There does not seem to be any relation between the symbiotic stars and the sequence D stars.

## 2.4.2 Radial Pulsation

There are several ways in which the present dataset can be used to test radial pulsation models:

### 2.4.2.1 The Phase Difference between Light and Velocity Curves

Minimum light and the mean of the velocity during its increase are relatively well defined for our sequence D stars, and are thus useful reference points allowing us to compare the phasing of the light and velocity curves. In order to examine their relative phases, a histogram of the phase difference between minimum light and mean rising velocity is shown in Figure 2.12. The phases of minimum light and mean rising velocity were obtained from the fits made to the light and velocity



**Figure 2.12:** Histograms of the difference between the phase of LSP minimum light and the phase of mean rising LSP radial velocity. The top panel shows the phase difference for MACHO  $M_B$ , the middle panel  $M_R$ , and the bottom panel OGLE  $I$ . Radial velocity is defined with respect to the observer: a positive radial velocity corresponds to matter moving away from the observer i.e. infalling to the centre of the star in a radial pulsation model.

curves. Each panel shows a strong peak of phase differences lying between 0 and 0.2 and there is little spread in phase.

Lebzelter et al. (2000) and Lebzelter & Hinkle (2002) find that for radially pulsating SRVs, the light lags the radial velocity by roughly 0.5 in phase, which means that minimum light occurs  $\sim 0.25$  in phase after the time of mean rising velocity. Our model SRV (Figure 2.2) shows that minimum light occurs close to 0.23 in phase after mean rising velocity. Our sequence D stars are significantly different. Taking the main peak of light-velocity phase differences in Figure 2.12 (values between  $-0.1$  and  $0.3$ ), the mean phase shift is 0.1, and the standard deviation is 0.08. More simply, minimum light usually occurs  $\sim 0.1$  in phase after mean rising velocity. Radial pulsation therefore may not be consistent with this aspect of the LSP phenomenon, although this is not a strong conclusion.



#### 2.4.2.2 The Shape of the Velocity Curve

During large amplitude radial stellar pulsation (as in Mira variables), a shock wave from the interior of the star causes the surface layers to rapidly accelerate outwards, and then settle back more slowly. This is also shown in the shape of the velocity curve of our low amplitude model SRV, Figure 2.2. The velocity curves of most of our sequence D stars show exactly the opposite of this behaviour: typically we find a rapid increase in radial velocity with a correspondingly slower decline (see Figure 2.3). In a radial pulsation model, this translates to a slow increase in stellar radius and a quick decrease. This has not been observed in any red giant stars known to be radially pulsating variables (e.g. Lebzelter, 1999; Hinkle et al., 1984, for SR variables and Mira variables respectively).

#### 2.4.2.3 Correlation of Velocity Amplitude with Light Amplitude, Magnitude and Period

The lack of correlation between velocity amplitude and light amplitude for the stars in our sample (see Figure 2.6) is an unexpected result for pulsation mechanisms as they would be expected to show a positive correlation between light and velocity amplitude (Hinkle et al., 1997). Additionally, correlations of velocity amplitude with luminosity and with period are expected for radially pulsating variables. However Figures 2.7 and 2.8 show that any correlations between these quantities in our sample are vague at best. We are unable to draw any conclusions from this in the context of radial pulsation.

#### 2.4.2.4 The Variation of Stellar Radius

The stellar radius can be calculated from our data in several ways. Our first method was to calculate  $R$  using the Stefan-Boltzmann equation  $L = 4\pi R^2 \sigma T_{\text{eff}}^4$ , with  $L$  and  $T_{\text{eff}}$  calculated from MACHO photometry (see Appendix A).

Examples of the variation of stellar radius calculated from the photometry,  $R_{\text{phot}}$ , can be seen in Figure 2.13. There is generally a clear periodic curve at the period of the LSP as well as a scatter due to the primary pulsation.

Variation of stellar radius can also be calculated from the velocity, using  $\Delta R = \int v dt$  where  $v$  is the fit to the velocity data made by FITALL. If we assume that the velocity changes are due to radial pulsation, then this gives the expected radius variation for radial pulsation,  $R_{\text{vel}}$ , where the resulting radius has been normalised to the median photometric radius. Here the velocity fit data was scaled by a factor of 1.4 to convert from observed to true pulsation velocity in red giants (Scholz & Wood, 2000; Wood et al., 2004). The radius change computed from the velocity fit is shown in Figure 2.13. Again it shows a clear periodic curve.

It is also possible to calculate stellar radius from the Stefan-Boltzmann equation using an effective temperature derived from the spectra, as opposed to the photometry (spectral  $T_{\text{eff}}$  derivation is described in Section 2.4.2.5). The luminosities at the times of the spectra were in this case calculated from the fits to  $M_B$ ,  $M_R$  and

( $M_B - M_R$ ) as described in Appendix A. The radius calculated in this manner,  $R_{\text{spec}}$ , can also be seen in Figure 2.13.

A histogram comparing the median values of  $R_{\text{phot}}$  and  $R_{\text{spec}}$  is shown in Figure 2.14. For both radius estimates, most stars have median radii lying between 100 and 200  $R_{\odot}$ . The median values for the entire sample for  $R_{\text{phot}}$  and  $R_{\text{spec}}$  are 135.4 and 132.1  $R_{\odot}$ .  $R_{\text{vel}}$  is not shown, as it is normalised to  $R_{\text{phot}}$ .

The radial amplitudes of our stars mostly lie between 3 and 60  $R_{\odot}$  for all three variations. The median amplitudes of the sample for  $\Delta R_{\text{phot}}$ ,  $\Delta R_{\text{spec}}$  and  $\Delta R_{\text{vel}}$  are 5.92, 5.62, and 40.02  $R_{\odot}$  respectively.

Figure 2.15 shows the distribution of radial amplitude  $\Delta R$  divided by period,  $P$ . This quantity is a more sensitive indicator of differences between stars and models than the amplitude itself. In a radially pulsating model, one would expect the amplitude,  $\Delta R$ , to be tightly correlated to the period if the velocity amplitudes are the same i.e.  $\Delta R/P$  would be a constant. Given that our stars show very similar velocity amplitudes (see Figure 2.4) we should expect tight, and similar, peaks for all three radius variations.

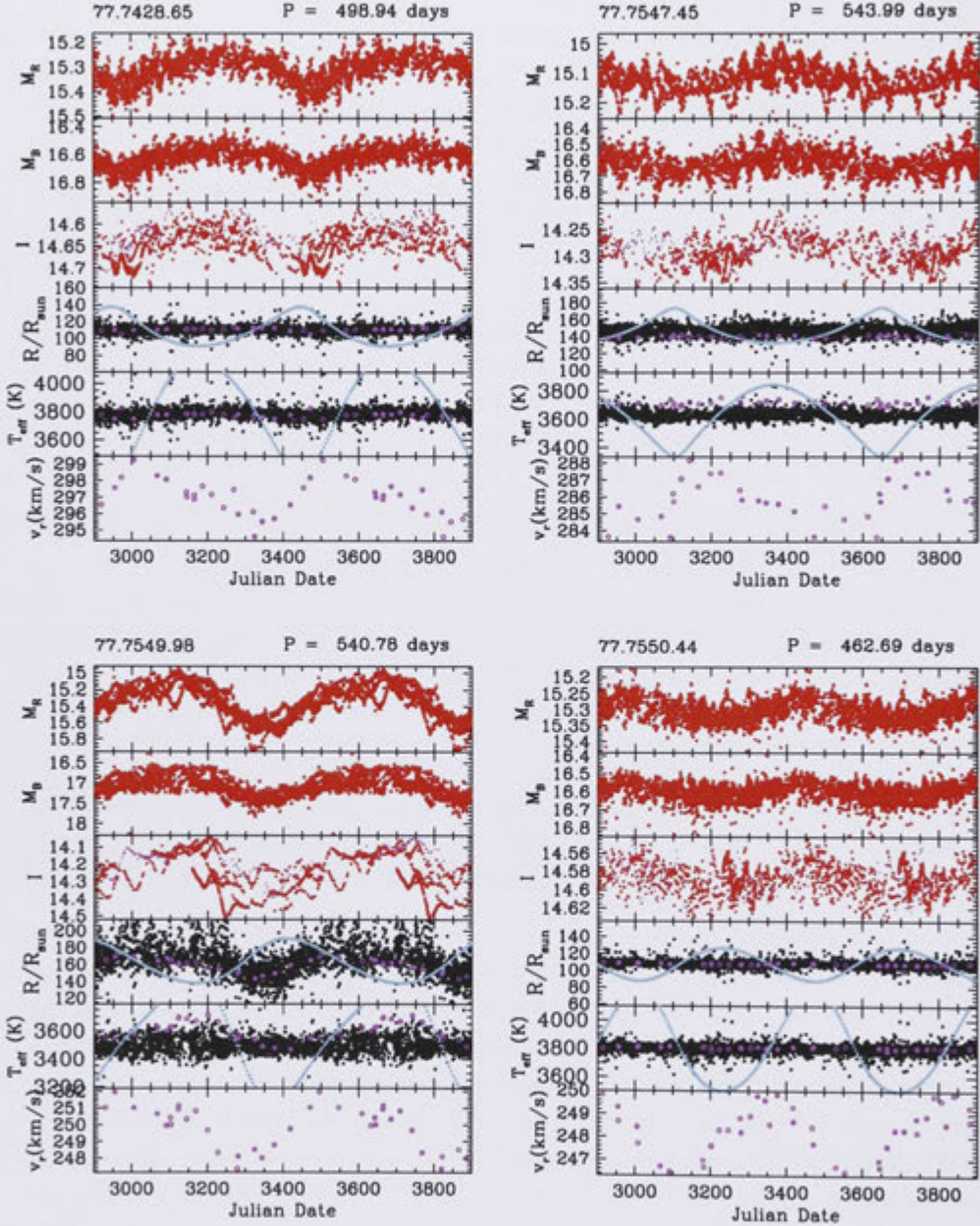
From Figure 2.15 it is clear that the distributions of  $\Delta R_{\text{phot}}/P$  and  $\Delta R_{\text{spec}}/P$ , are similar, but they are not the same as for  $\Delta R_{\text{vel}}/P$ .  $\Delta R_{\text{vel}}$  is computed assuming radial pulsation. Given that it appears that the three radius variations do not agree, the assumption that  $\Delta R$  is due to radial pulsation of the star is unlikely.

Figure 2.16 shows the distribution of  $\Delta R$  divided by  $R$ . For  $R_{\text{phot}}$  and  $R_{\text{spec}}$ , the fractional radius change is usually 10% or less. For  $R_{\text{vel}}$ , the fractional radius change is much larger, usually between 10 and 50%. Once again, the assumption that the measured radial velocity variations are due to radial pulsation does not seem to be correct.

A histogram comparing the phases of the three radius variations to the phase of the  $M_R$  light curve is shown in Figure 2.17. We compared the phase of minimum radius with the phase of minimum light, as these are both well-defined parts of the curves. In order to calculate these phases a Fourier series with four terms was fit to the radius curves. For the light curve, the previously-used Fourier fit was used (see Figure 2.3). Figure 2.17 shows that  $R_{\text{phot}}$  and  $R_{\text{spec}}$  both vary almost in phase with the light variation (phase differences generally  $\leq 0.1$ ). On the other hand,  $R_{\text{vel}}$  is more likely to be out of phase with the light (and consequently with the other radius variation estimates). Again, the assumption that the observed radius variations can be attributed to radial pulsation leads to inconsistencies.

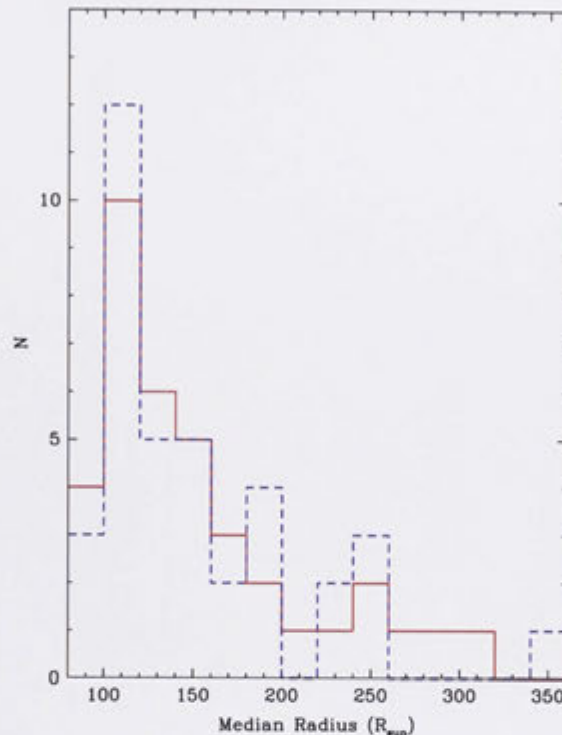
Using our model SRV (see Section 2.2.4) minimum radius occurs about 0.7 in phase before minimum light (Figure 2.2). Of our variations,  $R_{\text{vel}}$  is the most similar to this.  $R_{\text{phot}}$  and  $R_{\text{spec}}$ , whose phases agree well with each other, do not show the radius–light phase relation expected for radial pulsation.

Overall, the discrepancy between the variations of  $R_{\text{vel}}$  and the other two radius estimates suggests that radial pulsation is unlikely to be the cause of the LSPs.



**Figure 2.13:** Different properties of four typical sequence D stars plotted against Julian Date. Solid symbols denote values plotted at the date of measurement while open symbols are values that have been shifted forward or backward by one or more periods. *Top panel:* MACHO Red light curve. *Second panel:* MACHO Blue light curve. *Third panel:* OGLE  $I$  light curve. *Fourth panel:* Variation of  $R_{\text{phot}}$  (small black points), variation of  $R_{\text{vel}}$  (cyan curve) and variation of  $R_{\text{spec}}$  (large magenta points). *Fifth panel:* Variation of  $T_{\text{eff(phot)}}$  (small black points), variation of  $T_{\text{eff(spec)}}$  (large magenta points) and variation of  $T_{\text{eff(vel)}}$  (cyan curve). *Bottom panel:* Observed radial velocity. See text for details. Plots for the entire sample are available in the online version of this paper and in Appendix D.





**Figure 2.14:** Distribution of median values of  $R_{\text{phot}}$  (solid red line) and  $R_{\text{spec}}$  (dashed blue line).

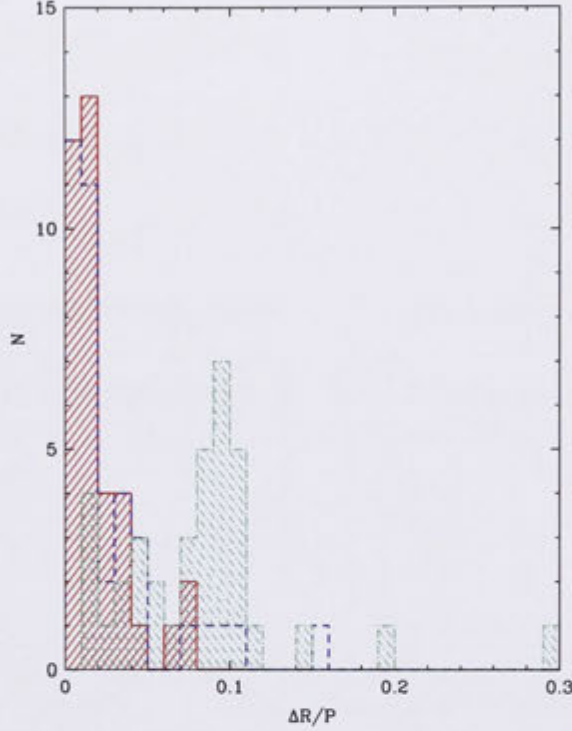
#### 2.4.2.5 The Variation of Effective Temperature

The variation of  $T_{\text{eff}}$  was calculated from the photometry, from the spectra and from the velocity fit.

The variation in the photometric  $T_{\text{eff}}$  ( $T_{\text{eff(phot)}}$ ), whose derivation is described in Appendix A, is shown in Figure 2.13.

$T_{\text{eff}}$  was also calculated using the depth of the TiO bandhead at 7054 Å ( $T_{\text{eff(spec)}}$ ). The depth was calculated as the ratio of the mean count level of a 4 Å band longward of the bandhead to the mean count level of a 4 Å band shortward of the bandhead, taking into account the fact that the LMC has an average velocity of 270 km s<sup>-1</sup>, leading to a longwards wavelength shift of 6.3 Å in the spectra.

In order to calculate the effective temperature from the TiO depth we calculated the depth of the TiO bandhead for 9 Wing Spectral Standard stars (private communication to Mike Bessell from Robert Wing). Then a quadratic fit was made to the TiO Depth–Spectral Type data. This quadratic fit was used to calculate the spectral types of our sequence D stars from their TiO depths, and the effective temperatures were then calculated using the Ridgway et al. (1980)  $T_{\text{eff}}$ –Spectral type



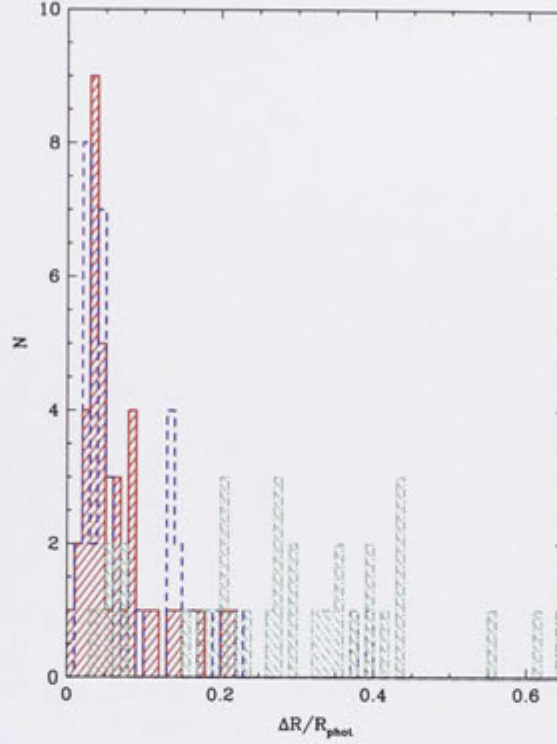
**Figure 2.15:** Distribution of radial amplitude/period for  $R_{\text{phot}}$  (solid red line, forward shading),  $R_{\text{spec}}$  (dashed blue line) and  $R_{\text{vel}}$  (dot-dashed green line, back shading).

relation. An example of the typical variation of  $T_{\text{eff(spec)}}$  in these stars can be seen in Figure 2.13.

Some of the warmer sequence D stars in our sample showed little to no evidence of TiO in their spectra, and so we were unable to include these in the  $T_{\text{eff(spec)}}$  calculation. However, good-quality velocity curves were not necessary for calculating  $T_{\text{eff(spec)}}$  so a number of stars previously discounted from the velocity studies were added in where consideration of radius and effective temperature was required. Overall there was a net increase in sample size from 30 to 37 (the stars added in were excluded only from the velocity amplitude, angle of periastron, eccentricity and velocity phase parts of this work).

We also calculated the effective temperature variation expected for radial pulsation,  $T_{\text{eff(vel)}}$ . This was calculated from the radius change computed for pulsation in Section 2.4.2.4, the luminosity calculated from the fits to the photometry, and the Stefan-Boltzmann equation. The variation of  $T_{\text{eff(vel)}}$  can be seen in Figure 2.13.

The distributions of the median values for each star of  $T_{\text{eff(phot)}}$  and  $T_{\text{eff(spec)}}$  are shown in Figure 2.18. Most stars have median effective temperatures lying between



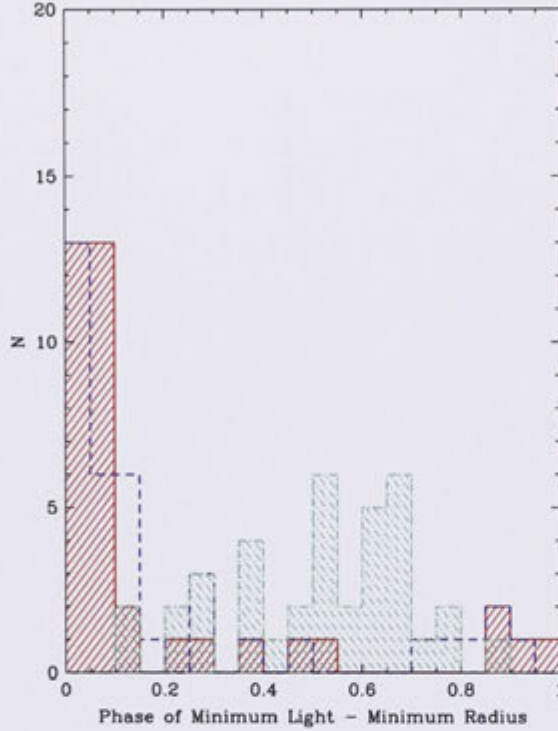
**Figure 2.16:** Distribution of relative radial amplitude for  $R_{\text{phot}}$  (solid red line, forward shading),  $R_{\text{spec}}$  (dashed blue line) and  $R_{\text{vel}}$  (dot-dashed green line, back shading).

3300 and 3800 K. The median values for the entire sample for  $T_{\text{eff(phot)}}$  and  $T_{\text{eff(spec)}}$  are 3662.9 and 3725.2 K.  $T_{\text{eff(vel)}}$  is not shown, as it is calculated from  $R_{\text{vel}}$ , which is normalised to  $R_{\text{phot}}$ .

Figure 2.19 shows the distribution of  $T_{\text{eff}}$  amplitude for the three variations. The amplitude distributions of  $T_{\text{eff(phot)}}$  and  $T_{\text{eff(spec)}}$  are both strongly peaked at lower values, but  $\Delta T_{\text{eff(vel)}}$  shows a much wider distribution, and tends towards much larger amplitudes. The amplitudes of  $T_{\text{eff(phot)}}$  and  $T_{\text{eff(spec)}}$  mostly lie between 20 and 200 K, but  $T_{\text{eff(vel)}}$  amplitudes tend to lie between 200 and 800 K. The median amplitudes of the sample are 42.3, 72.56, and 582.78 K for  $\Delta T_{\text{eff(phot)}}$ ,  $\Delta T_{\text{eff(spec)}}$  and  $\Delta T_{\text{eff(vel)}}$  respectively.  $T_{\text{eff(vel)}}$ , like  $T_{\text{eff(phot)}}$ , is a predicted temperature, whereas  $T_{\text{eff(spec)}}$  is measured from our data.  $T_{\text{eff(vel)}}$  has very large amplitudes in the context of radial pulsation. Adding this to the fact that  $T_{\text{eff(vel)}}$  does not agree with  $T_{\text{eff(spec)}}$  suggests that radial pulsation cannot explain the LSPs.

Figure 2.20 shows the relation of light amplitude to  $T_{\text{eff}}$  amplitude for both  $T_{\text{eff(phot)}}$  and  $T_{\text{eff(spec)}}$ . The graph shows that  $T_{\text{eff}}$  amplitude increases with increasing  $M_R$  amplitude, for both  $T_{\text{eff(phot)}}$  and  $T_{\text{eff(spec)}}$ . This is consistent with pulsation,





**Figure 2.17:** Distribution of phase of minimum light - phase of minimum radius for  $R_{\text{phot}}$  (solid red line, forward shading),  $R_{\text{spec}}$  (dashed blue line) and  $R_{\text{vel}}$  (dot-dashed green line, back shading).

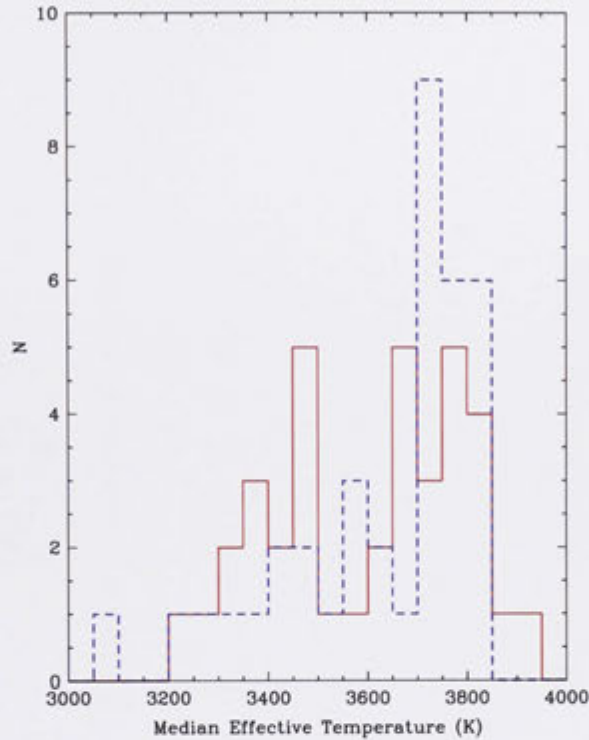
where a larger physical amplitude leads to larger luminosity variations and larger changes in effective temperature.

## 2.5 Discussion and Conclusions

### 2.5.1 The Movement of the Visible Surface of a Sequence D Star during its LSP

Possibly the most remarkable feature of the sequence D stars is the large change in the radial distance to the visible surface of a sequence D star as it passes through one LSP. By integrating the radial velocity with respect to time, we calculated in Section 2.4.2 a radius change for radial pulsation of between 3 and  $60 R_{\odot}$ , with the typical radius full amplitude being  $\sim 41 R_{\odot}$ . The typical median radius of a sequence D star is around  $135 R_{\odot}$ .

We can use this property to demonstrate just how unlikely radial pulsation is in

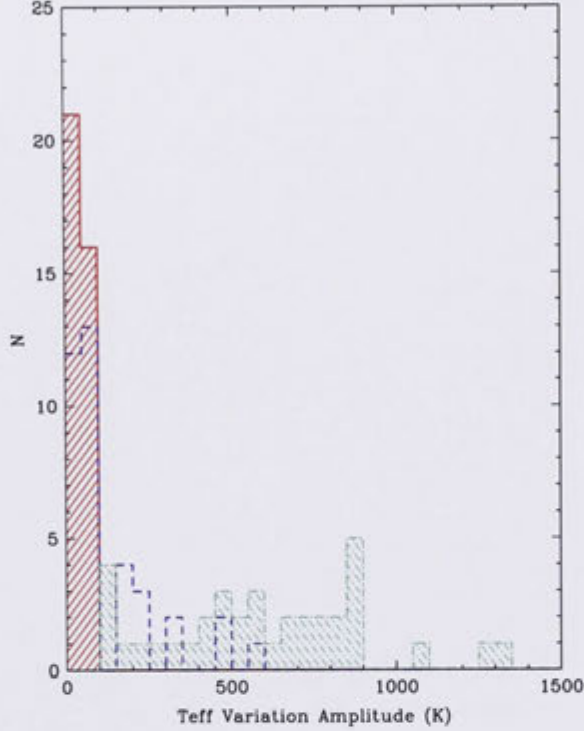


**Figure 2.18:** Distribution of median values of  $T_{\text{eff(phot)}}$  (solid red line) and  $T_{\text{eff(spec)}}$  (dashed blue line).

these stars. An amplitude of  $41 R_{\odot}$  in a  $135 R_{\odot}$  radially pulsating star corresponds to a fractional radius change of over 30% from minimum to maximum radius. These radial amplitudes are very large in the context of radial pulsation: fundamental-mode Mira variables pulsate with radius changes of the order of  $50 R_{\odot}$  (Ireland et al., 2004), but they have visible light amplitudes of  $\sim 6$  magnitudes, while typical sequence D stars have light amplitudes of  $\Delta M_R \leq 0.8$  mag. It seems unlikely that such a modest light change could be associated with so large a radius change, suggesting that radial pulsation is not the cause of LSPs.

This comparative analysis backs up a huge problem with the radial pulsation model which was raised in Section 2.4.2: the changes in radius would lead to changes in  $T_{\text{eff}}$  that are vastly greater than the directly observed changes from spectra or photometric colour.

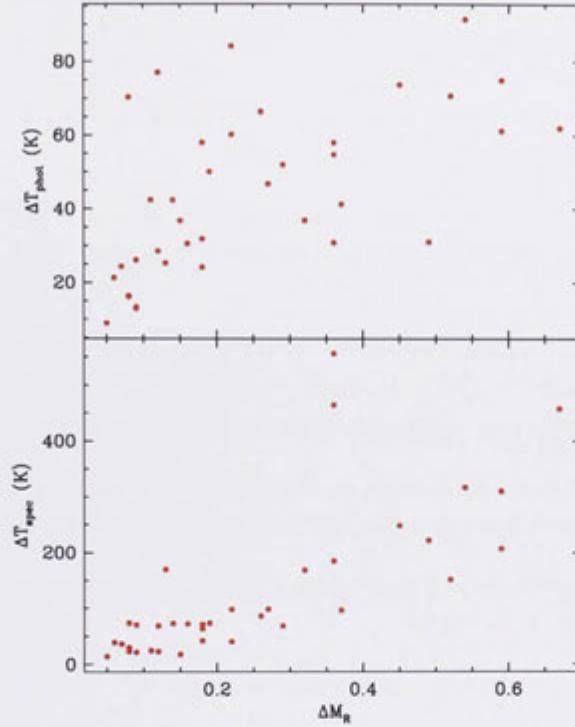
In addition to the problems with radial pulsation raised by our own data, there are also other problems raised by Wood et al. (2004): the length of the primary period does not vary during the LSP as expected; and to date there is no known mode of radial pulsation that has the required periods.



**Figure 2.19:** Distribution of amplitude of effective temperature variation for  $T_{\text{eff(phot)}}$  (solid red line, forward shading),  $T_{\text{eff(spec)}}$  (dashed blue line) and  $T_{\text{eff(vel)}}$  (dot-dashed green line, back shading). The higher end of the  $\Delta T_{\text{eff(vel)}}$  distribution has been cut off, in order to show greater detail at the peaks of  $\Delta T_{\text{eff(phot)}}$  and  $\Delta T_{\text{eff(spec)}}$ .

Wood et al. (2004) proposed nonradial pulsation as a possible cause for the LSPs. They showed that the best match to the observed periods is given by the  $g$  mode with  $n = 2$  and  $l = 2$ . In this case, the nett apparent radial velocity arises from some parts of the visible surface approaching while other parts are receding. Thus at a given position on the stellar surface, the velocity amplitudes and overall radial motions will need to be even larger than in the radial pulsation case. Given the large amplitudes calculated in this work for radial pulsation, nonradial pulsation would lead to distortions of the star that appear far too large to be credible, especially since  $g$  modes have significant amplitudes only in radiative regions (Wood et al., 2004).

It would therefore seem that the only way to generate the observed change in radial distance to the visible surface of a sequence D star is to have the star itself move, i.e. it must be in a binary system. Binary models, however, are inconsistent with various observational results described above. Most particularly, the non-uniform



**Figure 2.20:** *Top Panel:*  $\Delta T_{\text{eff(phot)}}$  plotted against  $\Delta M_R$ . *Bottom Panel:*  $\Delta T_{\text{eff(spec)}}$  plotted against  $\Delta M_R$ .

distribution of the angle of periastron and the low companion masses of these stars appear incompatible with a binary system model. The problem of the companion mass might be overcome if the companions were initially planets in eccentric orbits whose mass has been increased via accretion of material from the red giant. This would mean that although the companions currently have masses in the Brown Dwarf range, they were not born as Brown Dwarfs. To remove the problem of the non-uniform distribution of angle of periastron we would need to have an observational selection effect that rejects angles of periastron in the range  $0^\circ$ – $180^\circ$ , i.e. we would need an effect that masks the sequence D variation when periastron occurs with the smaller companion in front of the red giant. An effect which could produce this bias is difficult to imagine.

### 2.5.2 Attributes of the Long Secondary Period

As with past studies, we are unable to find definitive evidence for any model which explains the Long Secondary Periods in sequence D stars. To conclude, we therefore list all the currently known properties of LSPs. Any proposed model for LSPs should



be able to explain all of these attributes.

1. Stars exhibiting LSPs occupy a clearly defined period-luminosity sequence.
2. LSPs are of length  $\sim 250\text{--}1400$  days.
3. LSP light variation is not regular and minima in particular vary in depth from cycle to cycle (see Figure 2 of Wood et al. 1999).
4. The primary pulsation is visible in the light curve at all times throughout the LSP and the primary period does not significantly change with LSP phase (Wood et al., 2004).
5. The ratio of LSP to pulsation period is  $\sim 8\text{--}10$ . The shorter period variation lies usually on sequence B and is thought to be the first or second overtone radial pulsation (Wood et al. 1999; Ita et al., 2004; Fraser et al., 2005).
6. Lack of spectroscopic line broadening in observations of sequence D variables indicates that any rotational velocities are  $\leq 3 \text{ km s}^{-1}$  (Olivier & Wood, 2003).
7. The radial velocity curves show a characteristic shape: observed radial velocity increases quicker than it decreases.
8. The velocity amplitudes cluster tightly around  $3.5 \text{ km s}^{-1}$ .
9. The light-velocity phase shift for both the short-period and the LSP is  $\sim 0.25$ , with the light lagging the velocity. Minimum light is roughly aligned with mean rising velocity.
10. The ratio of colour to light variation of the LSP and primary oscillations are similar (Wood et al., 2004). Similarly, Derekas et al. (2006) showed that the ratio of blue to red amplitude of the LSP was similar to the ratio for stellar pulsation, and somewhat different from that due to ellipsoidal light variations.
11. There is no correlation between LSP light and velocity amplitude.
12. Stellar radius tends to be between  $100$  and  $200 R_{\odot}$ , with large radius variations of  $3\text{--}60 R_{\odot}$  (if it is assumed that the LSP is caused by radial pulsation).
13. The equivalent width of the  $\text{H}\alpha$  absorption line varies with the LSP, indicating chromospheric activity (Wood et al., 2004).

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# Evidence for Mass Ejection Associated with Long Secondary Periods in Red Giants

P. R. Wood and C. P. Nicholls, 2009, ApJ 707, 573

## Abstract

Approximately 30% of luminous red giants exhibit a Long Secondary Period (LSP) of variation in their light curves, in addition to a shorter primary period of oscillation. The cause of the LSP has so far defied explanation: leading possibilities are binarity and a nonradial mode of oscillation. Here, large samples of red giants in the Large Magellanic Cloud both with and without LSPs are examined for evidence of an 8 or 24  $\mu\text{m}$  mid-IR excess caused by circumstellar dust. It is found that stars with LSPs show a significant mid-IR excess compared to stars without LSPs. Furthermore, the near-IR  $J - K$  color seems unaffected by the presence of the 24  $\mu\text{m}$  excess. These findings indicate that LSPs cause mass ejection from red giants and that the lost mass and circumstellar dust is most likely in either a clumpy or a disk-like configuration. The underlying cause of the LSP and the mass ejection remains unknown.

## 3.1 Introduction

When red giants become more luminous than  $L \sim 1000 L_{\odot}$ , they begin to vary with periods of variation which fall on six physically distinct period-luminosity sequences<sup>1</sup> (Wood et al., 1999; Ita et al., 2004; Soszyński et al., 2007; Fraser et al., 2008). As well as these six sequences for the most luminous red giants, there is another sequence (known as sequence E) extending to lower luminosities and which is known

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<sup>1</sup>On these sequences, stars on the first ascent giant branch (FGB) have slightly longer periods than those on the asymptotic giant branch (AGB) at the same luminosity (Ita et al., 2004; Soszyński et al., 2007). Some authors designate the corresponding FGB and AGB sequences as distinct sequences.

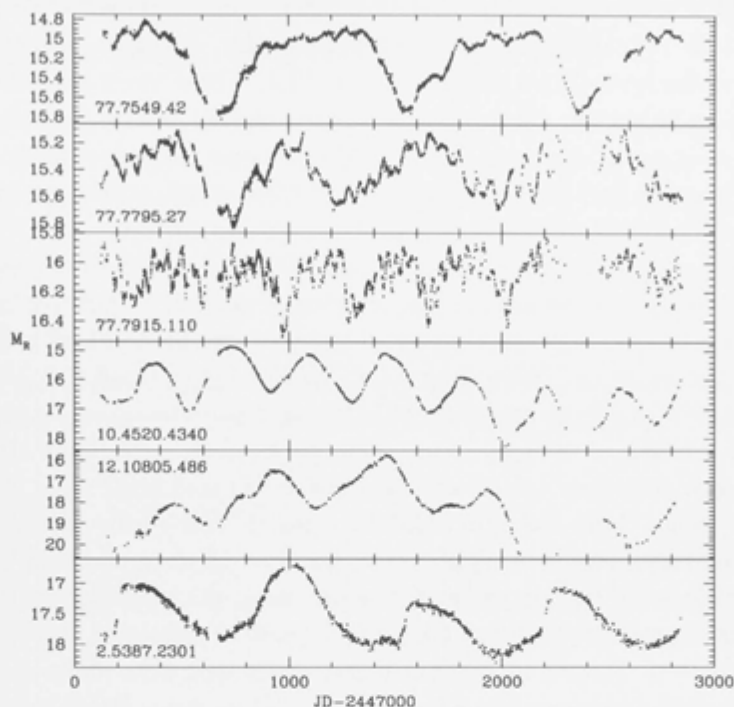
to consist of close binary systems exhibiting ellipsoidal light variations (Wood et al., 1999; Soszyński et al., 2004).

Among the six luminous sequences all but the longest in period can be explained by radial pulsation in the fundamental and overtone modes (Wood et al. 1999). The longest period sequence, sequence D, consists of stars that exhibit variations with a short period, usually corresponding to radial pulsation in a low overtone mode, as well as a Long Secondary Period (LSP). It is the LSPs that make up sequence D in the period–luminosity diagram for variable red giants. Approximately 30% of all luminous red giants have LSPs (Wood et al. 1999; Percy & Bakos, 2003; Soszyński et al., 2007; Fraser et al., 2008) so the LSP phenomenon is very common in the late evolution of low mass stars. Soszyński et al. (2007) suggest that LSPs can be seen at very low amplitude in up to 50% of luminous red giants. The LSPs also seem to occur in red supergiants (Stothers & Leung, 1971).

Since the period of the LSP is approximately 4 times longer than the period of the normal-mode radial fundamental mode, the LSP cannot be due to normal-mode radial pulsation. The most favoured explanations for the origin of LSPs are binarity and nonradial g-modes (Wood et al. 1999; Hinkle et al., 2002; Wood et al., 2004; Derekas et al., 2006; Soszyński, 2007; Hinkle et al., 2009), but these and other explanations for the LSPs all have significant problems (Wood et al., 2004; Nicholls et al., 2009). For example, stars exhibiting LSPs have velocity curves which generally are of similar shape and, in a binary model, this would indicate a favoured value for the angle of periastron of the orbit rather than the expected uniform distribution (Nicholls et al., 2009). In addition, the full amplitudes of the velocity curves are closely concentrated around  $3.5 \text{ km s}^{-1}$  (Nicholls et al., 2009) which implies the unlikely situation wherein all these stars have companions of a similar mass of  $\sim 0.09 M_{\odot}$ . The problem with the nonradial g-mode explanation for the LSPs is that g-modes, which have the correct periods, only have substantial amplitudes in radiative regions and red giants have convective envelopes with only a thin radiative layer on top (Wood et al., 2004). Currently, no satisfactory explanation for the LSPs exists.

Several of the suggested explanations for the LSPs in red giants involve circumstellar dust. The change in visible light associated with the LSP is typically of a rather irregular nature, and the light variation can be large, up to a factor of two. In the binary model, it has been suggested that the light change could be due to a large dust cloud orbiting with the companion and obscuring the red giant once per orbit (Wood et al. 1999). Another possible explanation for the LSPs (Wood et al. 1999) involves semi-periodic dust ejection events such as those predicted by theoretical models of AGB stars (Winters et al., 1994; Hoefner et al., 1995).

Confirmation that dust was involved with the LSP phenomenon would be obtained if these stars showed a mid-infrared flux excess due to absorption of stellar light by circumstellar dust followed by re-radiation in the mid-IR. Both Hinkle et al. (2002) and Olivier & Wood (2003) examined the mid-IR colors of small samples of stars with LSPs in the solar vicinity using IRAS data. They found no evidence for a mid-IR excess that would indicate the presence of unusual amounts of circumstellar dust. With the completion of the Spitzer Space Telescope SAGE survey in the



**Figure 3.1:** Typical light curves of sequence D stars (top 3 panels) and of high mass loss rate stars removed from the Fraser et al. (2008) list of sequence D stars (lower 3 panels).

LMC (Meixner et al., 2006; Blum et al., 2006), it is now possible to search for the presence of a mid-IR excess in large samples of stars with LSPs, good contemporary light curves and a known distance. We now describe such a search.

## 3.2 Selection of Samples of Variables

The sample of variable stars examined here is taken from Fraser et al. (2008) who classified the luminous red giant variables in the LMC according to whether they belonged to sequence D or sequences 1–4<sup>2</sup>. The sequence D stars exhibit light variations at both a primary period, which is usually on sequence 2 or sequence 3, and a Long Secondary Period, which falls on sequence D. Examples of the light curves of typical sequence D stars are shown in the top three panels of Figure 3.1.

The sequence D sample of Fraser et al. (2008) was refined in a number of ways. To be retained in our sample of sequence D stars, a star was required to show both the quasi-periodic LSP as well as a shorter primary period. In an initial examination of the light curves of the sequence D stars in the catalog of Fraser et al. (2008), we found

<sup>2</sup>Other authors use sequences C, C', B and A in place of sequences 1–4, respectively, of Fraser et al. (2008). In addition, Soszyński et al. (2007) find a shorter period sequence that would be sequence 5 in the notation of Fraser et al. (2008).

stars which have light curves that show a smooth, large amplitude variation as well as a variation of mean magnitude over very long timescales. Examples of their light curves are shown in the lower three panels of Figure 3.1. These are stars with large-amplitude, Mira-like pulsation, high mass loss rates and thick circumstellar dust shells and they belong on sequence 1. The dust shells cause them to appear fainter in the visible and near-IR part of the spectrum than they would appear without the dust shell. In the  $(K, \log P)$  plane, they thus lie below sequence 1, and they can take a position near or on sequence D (e.g. Wood, 2003). In order to decrease the number of light curves to be examined to test for genuine sequence D characteristics, we restricted our sample of sequence D stars to have a value for the LSP falling on the main body of the sequence, defined by  $2.1 < \log P - (14 - K)/4.2 < 2.4$ . This eliminates considerable numbers of the dusty, Mira-like stars assigned to sequence D by Fraser et al. (2008), as well as some sequence E stars. The light curves of all remaining stars within the main body of sequence D and with  $K < 12$  were inspected and the dusty, Mira-like stars and sequence E stars were removed. We limited our detailed examination of light curves to  $K < 12$  as it is these brighter stars that are used later in the paper for the comparison of mid-IR properties. A small number of other stars that did not have the required sequence D light curve shape were also removed: these were normal semi-regular variables without obvious LSPs that are typical of sequences 2 and 3, and several R Coronae Borealis stars. In total, we removed 105 stars from the original sequence D sample. Finally, about 5% of stars appeared twice in the lists of Fraser et al. (2008) under different MACHO names (because they were in overlapping parts of different MACHO fields): only one entry was retained for these stars.

Our aim is to see if unusual amounts of circumstellar dust are associated with stars exhibiting LSPs. In order to make such a test, we need a sample of stars that are identical to the stars with LSPs except that they do not have LSPs. This comparable sample is the combined group of stars on sequence 2 and sequence 3 i.e. stars with an oscillation similar to the primary oscillation period of the LSPVs. Hereinafter, we will refer to the variable stars on sequence D as LSPVs and the stars on sequence 2 and sequence 3 as SRVs (semi-regular variables).

Looking at the light curves of the LSPVs and SRVs, it is clear that some variations are of low amplitude and therefore the periods, and hence the variability sequence, are not well determined. Fraser et al. (2008) determined periods by two methods - a Fourier analysis and a SuperSmoother method. In order to get samples of LSPVs and SRVs with reliable sequence determinations, we chose a subsample of the LSPVs and SRVs in which the SuperSmoother and Fourier period agreed to 5%. We call these the P5 samples. The stars in the P5 samples tend to have larger amplitudes and more regular variations than the remaining stars in the complete samples. The amplitude distribution of the two samples is shown later, in Section 3.3.3. For the stars with  $K < 12$  that are examined in detail in this paper, there are 4807 LSPVs and 4568 SRVs in the complete samples and 1568 LSPVs and 971 SRVs in the P5 samples.

### 3.3 Testing for Circumstellar Dust using Mid-IR Fluxes from the SAGE Survey

Since cool circumstellar dust emits preferentially in the mid-IR (longward of  $\sim 5\mu\text{m}$ ) while the stellar photosphere emits mainly in the near-IR (shortward of  $\sim 3\mu\text{m}$ ), a large ratio of mid-IR flux to near-IR flux can be used as an indicator of circumstellar dust. The  $K - [24]$  color is a sensitive indicator of cool circumstellar dust, especially very cool dust with a temperature of  $\sim 200\text{ K}$ , while the  $K - [8]$  color would be more sensitive to slightly warmer dust with  $T \sim 400\text{ K}$ . A problem with the  $K - [24]$  color is that the SAGE survey only detected a  $24\mu\text{m}$  flux from a small fraction of the bright red giants in the LMC. On the other hand, and  $8\mu\text{m}$  flux was detected for most bright red giants. We now discuss both of these options.

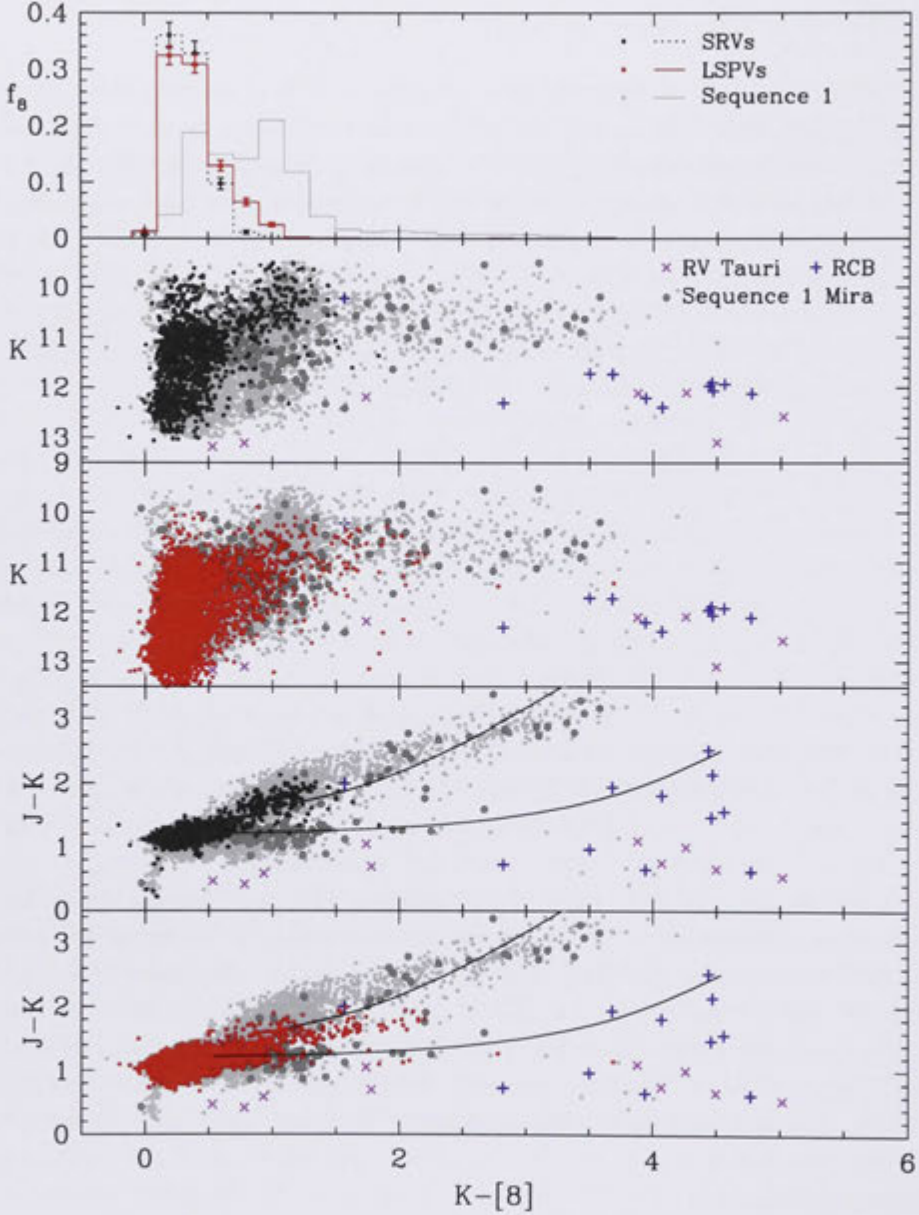
#### 3.3.1 The $K - [8]$ Color

In Figure 3.2 we show  $K$  and  $J - K$  plotted against  $K - [8]$  for the LSPVs and the SRVs in the P5 samples. Also shown are stars on sequence 1: these are fundamental mode radial pulsators and they include the Mira variables and large amplitude, high mass loss rate, dust enshrouded long period variables.

It is well known that, in the LMC, red giant stars with  $J - K \gtrsim 1.4$  are mostly carbon stars and those with  $J - K \lesssim 1.4$  are oxygen-rich M or K stars (Cioni & Habing, 2003). The separation of the C- and O-rich stars is seen in the  $(K - [8], J - K)$  diagrams in the lower two panels of Figure 3.2: the separation is seen most easily for the grey points of sequence 1. These diagrams also show that there is a long tail of sequence 1 stars extending from the clump of C stars around  $(K - [8], J - K) = (1.1, 1.8)$  to redder  $K - [8]$  and redder  $J - K$  colors. This tail contains many C-rich Mira variables, defined as sequence 1 variables with a MACHO blue amplitude greater than 2.5 magnitudes. However, the Mira variables are not confined to this region of the  $(K - [8], J - K)$  diagram. There are even more of them lower in the diagram with  $J - K < 1.4$  and  $K - [8] < 1.5$ : these are O-rich Mira variables.

Mira variables are AGB stars of relatively high mass loss rate with roughly spherical shells, perhaps with some clumpiness (see Olofsson 2004 for a review of the evidence for clumpiness in Mira winds). In order to get some idea of the positions of stars with spherical mass loss shells in the  $(K - [8], J - K)$  diagram, models of such stars have been made with the code DUSTY (Ivezic et al., 1999) which is designed to model the spherical dust envelopes of mass-losing AGB stars. Two series of models were made, one for C stars and one for O-rich stars. The C star models had a central star which was assumed to be a blackbody of temperature 2200 K and the grains in the stellar wind emanating from the central star were assumed to be 50% amorphous carbon and 50% SiC. The O-rich models had a central blackbody with  $T = 2700\text{ K}$  and warm silicate dust in the stellar wind. In both sets of models, the inner temperature of the dust shell was assumed to be 1000 K, and the model series had a range of  $V$  band optical depths from 0.1 to 10, corresponding to mass loss rates of approximately  $2 \times 10^{-7}$  to  $7 \times 10^{-6} M_{\odot} \text{ yr}^{-1}$  for a star with  $L = 5000 L_{\odot}$ . These are simple approximations that do not allow for variation of





**Figure 3.2:**  $K$  and  $J - K$  plotted against  $K - [8]$  for the P5 samples of LSPVs (small red points, panels 1 and 3 from the bottom) and SRVs (small black points, panels 2 and 4 from the bottom). Stars on sequence 1 are shown as small grey points. The large amplitude Mira variables belonging to sequence 1 are shown as larger points that are a darker shade of grey. The magenta crosses are the 10 RV Tauri stars in the LMC studied by Alcock et al. (1998) that have  $J$ ,  $K$  and  $[8]$  magnitudes while the blue plus signs are the 11 RCB stars in the LMC studied by Alcock et al. (2001). The lines in the bottom two panels are model AGB stars with spherical dust shells of increasing optical depth (see text). The top panel shows the fraction of the O-rich ( $J - K < 1.4$ ) SRVs and LSPVs stars brighter than  $K = 12$  which lie in  $K - [8]$  color bins of width 0.2 magnitudes: one-sigma error bars are given. Also shown in the top panel is the distribution of sequence 1 stars, both C and O-rich.

the stellar temperature, inner boundary temperature or grain composition as the stars evolve. They are meant to provide a general idea of how mass-losing AGB stars evolve in the  $(K - [8], J - K)$  diagram rather than a precise prediction.

The upper curve in the lower two panels of Figure 3.2 represents the sequence of model C stars with increasing mass loss rate. This corresponds, within the simple model approximations used here, to the tail of sequence 1 stars in the upper parts of the  $(K - [8], J - K)$  diagrams. This tail thus represents the evolutionary sequence of C stars with spherical mass loss shells of increasing mass loss rate (see Groenewegen et al. 2007 for detailed mass loss rate estimates for these stars). The lower curve in the bottom two panels of Figure 3.2 is the equivalent curve for O-rich stars. It can be seen that many O-rich Miras fall on this curve.

The position of the high mass loss rate AGB stars with spherical shells contrasts with the position of the RV Tauri stars shown in Figure 3.2. The latter can have very large  $K - [8]$  colors but their  $J - K$  colors are similar to the colors of stars with unobscured photospheres. Since RV Tauri stars are luminous post-AGB stars containing a dusty circumbinary disk which radiates in the mid-IR (de Ruyter et al., 2005), a low  $J - K$  and a large  $K - [8]$  is likely to indicate a star with a dusty disk. This picture is consistent with the  $J - K$  colors of the R Coronae Borealis (RCB) stars, which are all C-rich. The dust associated with them is in neither a disk nor a spherical shell but arises from the ejection of puffs of dust in random directions, leading to a highly non-spherical dust distribution (Clayton, 1996). The  $J - K$  colors of the RCB stars scatter between the  $J - K$  colors of the RV Tauri stars and the high mass loss rate C-rich spherical shell sources, as expected in this model since the line of sight to some RCB stars would contain dust clouds while in other stars the photosphere would be seen unobscured.

The considerations above allow us to interpret the positions of the SRVs and LSPVs in Figure 3.2. The great majority of the oxygen-rich SRVs ( $J - K < 1.4$ ) have  $K - [8] < 0.7$ , indicating very little mid-IR excess and low mass loss rates. Similarly, the C-rich SRVs lie mostly in the domain of the C stars with low mass loss rates on sequence 1. This contrasts with the LSPVs, both C- and O-rich, many of which appear to show some evidence for a  $K - [8]$  excess. For the C stars, the large fraction of LSPVs with a  $K - [8]$  excess can be clearly seen by comparing the lower two panels of the Figure. The top panel of Figure 3.2 shows the  $K - [8]$  color distribution of the O-rich SRVs and LSPVs more quantitatively: the larger fraction of LSPVs with  $K - [8] > 0.7$  is clearly seen (11% of LSPVs have  $K - [8] > 0.7$  compared to 2.3% of SRVs). A two sample K-S test gives a probability less than  $3.8 \times 10^{-7}$  that the SRVs and the LSPVs in the histograms come from the same underlying distribution, i.e. the higher fraction of LSPVs with  $K - [8] > 0.7$  is extremely unlikely to be a statistical artifact. Note that in the histograms shown in Figure 3.2, and in subsequent figures, we have restricted the samples of stars to those with  $K < 12$  since most of the stars that have detectable 8 and  $24\mu\text{m}$  fluxes have  $K < 12$ . In addition, first ascent giant branch stars are excluded by the restriction  $K < 12$ . At  $8\mu\text{m}$ , we find that 99.4% of LSPVs (1561 stars), 99.8% of SRVs (969 stars) and 99.5% of sequence 1 variables (3964 stars) with  $K < 12$  were detected.

There is one notable feature of the  $(K - [8], J - K)$  diagram for LSPVs. The

reddest C-rich LSPVs have  $J - K$  colors that are similar to those of the unreddened C stars, and they are distinctly less than the  $J - K$  colors of the C-rich circumstellar shell sources in sequence 1 which have the same  $K - [8]$  color. There are also a few O-rich LSPVs with large  $K - [8]$  colors that fall near the RV Tauri stars. This suggests that mass loss from LSPVs is not spherically symmetric and that the dust may be in a circumstellar disk or some other non-spherical distribution. These results become much clearer when using the  $24\mu\text{m}$  measurements from the SAGE survey, as we will now show.

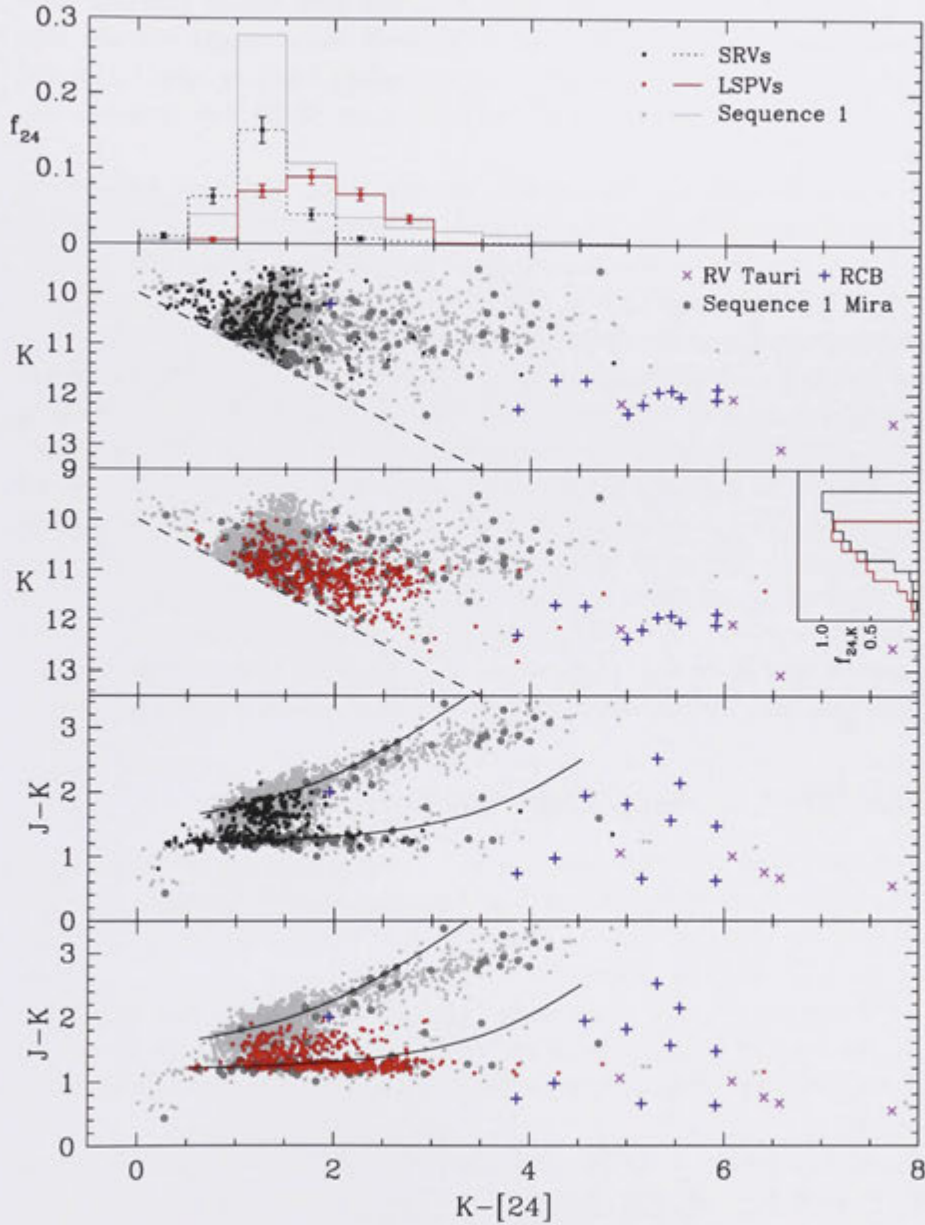
### 3.3.2 The $K - [24]$ Color

Figure 3.3 shows a plot similar to Figure 3.2 but using the  $K - [24]$  color. It is immediately obvious from comparing Figures 3.2 and 3.3 that only a small fraction of the sample was detected at  $24\mu\text{m}$ . In the P5 samples, for objects brighter than  $K = 12$ , 27% of LSPVs (424 stars) and 28% of SRVs (269 stars) were detected at  $24\mu\text{m}$  whereas essentially all stars were detected at  $8\mu\text{m}$ . For the sequence 1 variables, 52% (2077 stars) brighter than  $K = 12$  were detected at  $24\mu\text{m}$ .

Comparing the LSPV and SRV samples in the lower four panels of Figure 3.3, it appears that the LSPVs are much more likely to show a  $K - [24]$  excess than the SRVs. This is confirmed by the histogram of  $K - [24]$  colors in the top panel of the Figure where it can be seen that a significantly larger fraction of LSPVs with  $K < 12$  have  $K - [24] > 1.5$  (72% of LSPVs have  $K - [24] > 1.5$  compared to 19% of SRVs). A two sample K-S test gives a probability less than  $2.0 \times 10^{-42}$  that the SRVs and the LSPVs in the histograms come from the same underlying distribution.

Given the stronger mid-IR excess exhibited by the LSPVs, one would expect a larger fraction of LSPVs to be detected at  $24\mu\text{m}$  than SRVs yet, as noted above, similar fractions of LSPVs (27%) and SRVs (28%) were detected. This is explained by the inset histogram in the middle panel of Figure 3.3 which shows the detection fraction as a function of  $K$  magnitude. It is seen that the SRVs extend to brighter  $K$  magnitudes than the LSPVs and that there is almost 100% detection of these brighter objects even though they do not have large  $K - [24]$  values. Most importantly, at all  $K$  magnitudes where the LSPV and SRV samples both exist, the LSPV detection fraction is higher than the SRV detection fraction.

The C stars and the O-rich stars in the lower two panels of Figure 3.3 fall in distinct groups separated by the line  $J - K = 1.4$ , the C stars lying above this line. As with Figure 3.2, the  $J - K$  colors of the C-rich LSPVs in Figure 3.3 are smaller than those of the C-stars on sequence 1 which have high mass loss rates in spherical winds. The picture for the O-rich stars is less clear. On the one hand, there is a very large group of O-rich LSPVs with  $J - K < 1.4$  but red  $K - [24]$  colors which fall below the line of DUSTY models of increasing mass loss rate in spherical shells. This group of O-rich LSPVs seems to follow the sequence occupied by the RV Tauri stars with circumstellar disks. On the other hand, some sequence 1 Mira variables also follow this sequence while others have larger  $J - K$  values as suggested by the spherically symmetric models. It is not clear whether this diversity



**Figure 3.3:** The same as Figure 3.2 but using the  $K - [24]$  color rather than the  $K - [8]$  color for the P5 samples. The dashed line marks the  $24\mu\text{m}$  magnitude limit ( $[24] = 10$ ) of the SAGE survey. The inset in the third panel shows the fraction of the P5 sample of LSPVs (red histogram) and SRVs (black histogram) detected at  $24\mu\text{m}$  as a function of  $K$  magnitude. The histograms of LSPVs and SRVs in the top panel include both C and O-rich stars.



of behaviour is because the winds in Miras are not all spherically symmetric or if it is because the models are too simplistic<sup>3</sup>. However, the reddest LSPVs with  $K - [24] > 4$  appear similar to the RV Tauri stars and they almost certainly have a non-spherically symmetric dust distribution. Overall, these results indicate that not only do the LSPVs produce more dust than equivalent SRVs without LSPs, but this dust appears to be in a non-spherical distribution about the star, possibly in a circumbinary disk.

The numbers of stars in the P5 samples are moderate. However, the results shown above are confirmed by the larger number of stars in the complete samples, as shown in Figure 3.4. In the complete samples, for objects brighter than  $K = 12$ , 31% of LSPVs (1482 stars) and 28% of SRVs (1285 stars) were detected at  $24\mu\text{m}$ . These fractions are similar to the detection fractions in the P5 samples.

One question that arises is whether the stars that show a  $K - [24]$  excess are also the stars that show a  $K - [8]$  excess. We note that there are only 3 stars in the combined complete samples with a  $24\mu\text{m}$  detection but not an  $8\mu\text{m}$  detection, so that it is possible to compare the  $K - [24]$  excess with the  $K - [8]$  excess for essentially all stars. This is done in Figure 3.5 where  $K - [24]$  is plotted against  $K - [8]$  for all stars with  $K < 12$  in the complete samples. There are clearly two sequences in Figure 3.5, one for C stars and one for O-rich stars. Both sequences show a correlated increase in  $K - [8]$  color with  $K - [24]$  color. Thus stars with a  $K - [24]$  excess do also show a  $K - [8]$  excess. Note that the LSPVs have a higher fraction of red stars than the SRVs (as already demonstrated in Figures 3.2–3.4).

### 3.3.3 The Effect of Amplitude on $K - [24]$ Color

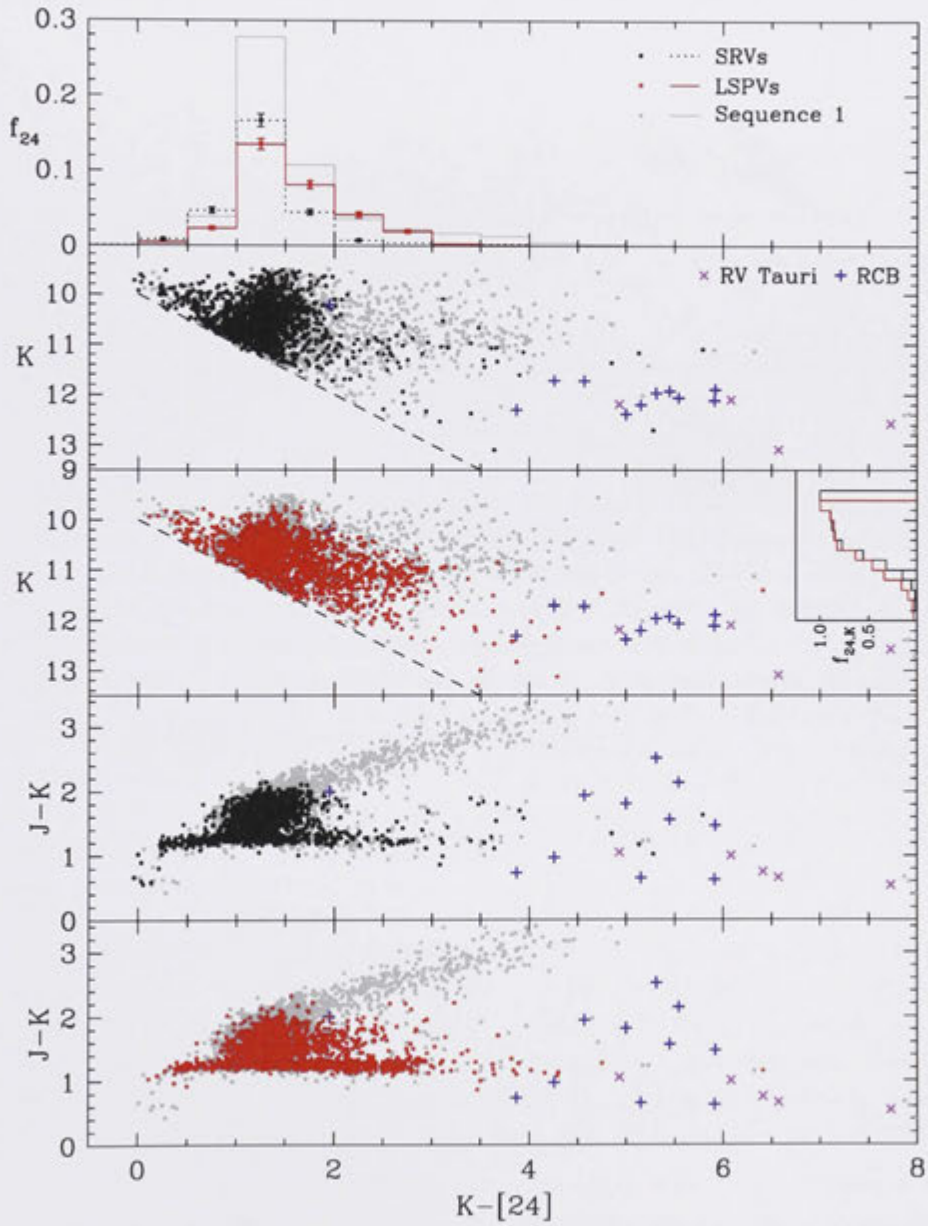
It has been shown above that the existence of a Long Secondary Period in a red giant seems to induce extra circumstellar dust formation. In this situation, it might be expected that the infrared excess caused by dust would depend on the light amplitude of the LSP. We now examine this suggestion.

Figure 3.6 shows the  $K - [24]$  color plotted against the MACHO blue amplitude for LSPVs in the P5 and complete samples. We used the MACHO blue amplitude rather than the MACHO red amplitude as the phase coverage is generally better in blue than in red.

There is a slight increase of the  $K - [24]$  color with MACHO blue amplitude. A least squares fit gives  $K - [24] = 0.73\text{Amp}(M_B) + 1.47$  for the complete sample and  $K - [24] = 0.90\text{Amp}(M_B) + 1.20$  for the P5 sample. In both cases, the *rms* scatter of the  $K - [24]$  color about the fit is 0.50 magnitudes. Given this large scatter, a wide range in  $K - [24]$  color can be found at any given light amplitude. We conclude that the light amplitude does not seem to be an important factor in determining the amount of mass loss and the mid-IR excess of LSPVs.

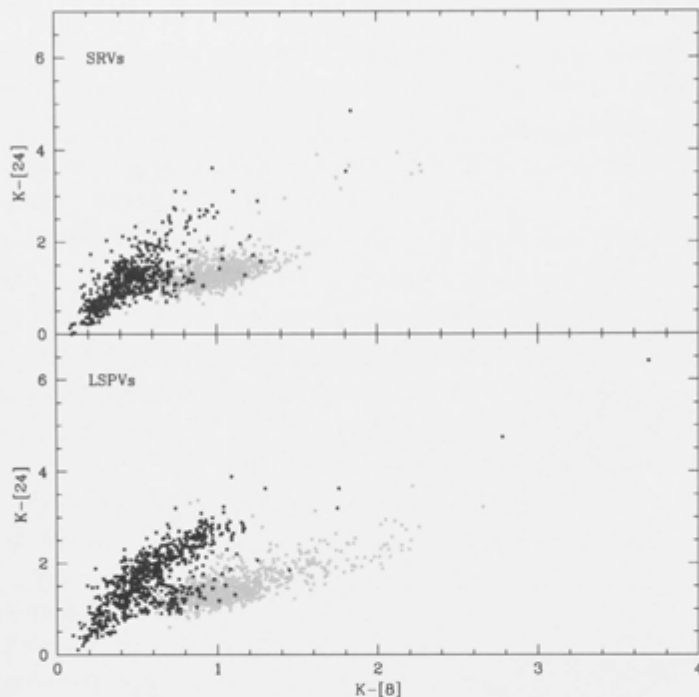
The top panel of Figure 3.6 indicates that the LSPVs that are in the P5 sample

<sup>3</sup>The O-rich models of Groenewegen (2006) follow the same general behaviour as the DUSTY models shown here but they tend to be 0.5 to 1 mag redder in  $K - [24]$  for the higher mass loss rates.



**Figure 3.4:** The same as Figure 3.3 but for stars detected at  $24\mu\text{m}$  in the larger, complete samples.





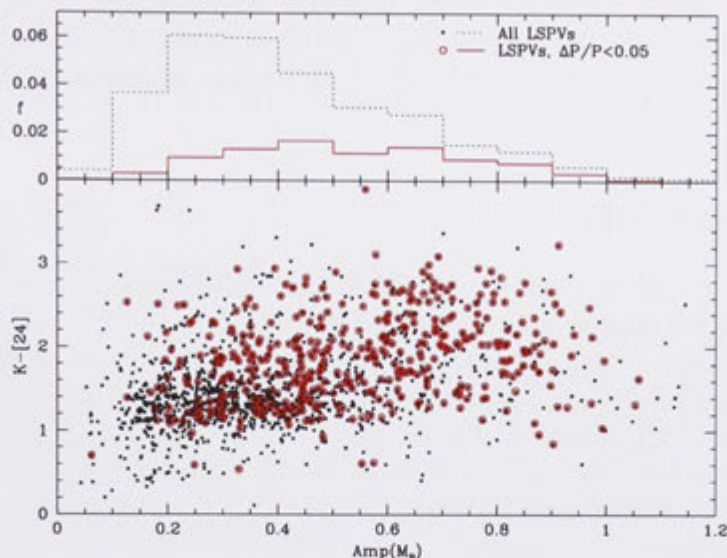
**Figure 3.5:**  $K - [24]$  plotted against  $K - [8]$  for the stars that have  $K < 12$  in the complete samples of LSPVs and SRVs. The black points are stars with  $J - K < 1.4$  (O-rich star candidates) while the grey points are stars with  $J - K \geq 1.4$  (C star candidates).

have larger average amplitudes than those in the complete sample. This confirms our assertion in Section 3.2 .

It would be interesting to see if there was any correlation between the velocity amplitude of the LSP given in Nicholls et al. (2009) and the  $K - [24]$  color. Note that the radial velocity amplitude associated with the LSPs does not show any correlation with light amplitude (Nicholls et al., 2009). There are 16 LSPVs in the group of stars studied by Nicholls et al. (2009) that have  $K - [8]$  colors and 6 with  $K - [24]$  colors. A plot of the  $K - [8]$  and  $K - [24]$  colors against velocity amplitude for these small samples of stars did not show any particular correlation.

### 3.4 Summary and Conclusions

We have shown that luminous red giant stars that exhibit Long Secondary Periods have larger mid-IR fluxes than similar stars without LSPs. This suggests that the LSP induces additional mass loss from the red giant, with consequent dust formation and an increase in the mid-IR flux. The mid-IR flux excess is only weakly dependent on the amplitude of the light variation of the LSP. A comparison of the near-IR  $J - K$  color with the mid-IR  $K - [24]$  and  $K - [8]$  colors indicates that the dust is not in



**Figure 3.6:** The  $K - [24]$  color plotted against the MACHO blue amplitude of the LSP for LSPVs with  $K < 12$  (bottom panel). Black dots show stars in the complete sample while stars also in the P5 sample are surrounded by red circles. The histogram in the top panel shows the fraction of all LSPVs which have  $K < 12$  and a detected  $24\mu\text{m}$  flux in the P5 sample (red line) and the complete sample (black dotted line).

a spherically symmetric distribution, and is perhaps in a disk.

Although dust is associated with the LSP phenomenon, it is still not clear what causes the LSP in the first place. In a binary model, where the velocity curves indicate predominantly eccentric orbits (Nicholls et al., 2009), mass transfer from the red giant near periastron could lead to a circumbinary disk. A non-radial pulsation mode of low degree could also produce non-spherical mass loss and a non-spherical dust distribution. The semi-periodic dust ejection events predicted by Winters et al. (1994) and Hoefner et al. (1995) produce, and indeed require, circumstellar dust. However, this phenomenon has not been found to occur in theoretical models at the low luminosities where many of the LSPs are observed (even below the tip of the FGB). Furthermore, it is also not clear why the photospheric velocity should vary with the LSP for this purely circumstellar process.

One additional characteristic of LSPVs is that they have a chromosphere which varies with the LSP (Wood et al., 2004). It is likely that both the chromosphere and the excess circumstellar dust are manifestations of the influence of the LSP phenomenon on matter above the stellar photosphere. Magnetic effects are a possible source of the chromosphere, but a search for magnetic fields in two solar-vicinity LSPVs has put an upper limit of 100 Gauss on magnetic fields covering more than about 10% of the surface of these stars (Wood et al., 2009). Currently there is no evidence that magnetic fields are the source of the chromosphere.

In summary, we have shown here that the LSP phenomenon produces excess

circumstellar dust compared to stars without LSPs. Unfortunately, since all the postulated models for the LSP are potentially capable of causing mass ejection, the present detection of excess dust around LSPVs does not help us distinguish between the various models.

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# Ellipsoidal Variability and the Difference between Sequence D and E Red Giants

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## Abstract

We have studied a sample of Large Magellanic Cloud red giant binaries that lie on sequence E in the period–luminosity plane. We show that their combined light and velocity curves unambiguously demonstrate that they are binaries showing ellipsoidal variability. By comparing the phased light and velocity curves of both sequence D and E variables, we show that the sequence D variation – the Long Secondary Period – is not caused by ellipsoidal variability. We also demonstrate several further differences between stars on sequences D and E. These include differences in velocity amplitude, in the distribution of eccentricity, and in the correlations of velocity amplitude with luminosity and period. We also show that the sequence E stars, unlike stars on sequence D, do not show any evidence of a mid-infrared excess that would indicate circumstellar dust.

## 4.1 Introduction

Long Period Variables (LPVs) are known to fall on different sequences in the period–luminosity plane (Wood et al., 1999; Kiss & Bedding, 2003; Ita et al., 2004; Soszyński et al., 2004a; Fraser et al., 2005; Soszyński et al., 2007; Fraser et al., 2008). One of these sequences, known as sequence E, is thought to consist of red giants in close binary systems showing ellipsoidal variability, although this has not been unambiguously demonstrated. A small number of the binaries appear to be eclipsing and others appear to have unexpectedly eccentric orbits, based on their light curve shape (Soszyński et al., 2004b).

A star in a close binary will have its Roche Lobe distorted by the tidal influence of its orbiting companion. When the star begins to fill its Roche Lobe it takes on an elongated, or ellipsoidal shape, becoming an ellipsoidal variable. The velocity



**Table 4.1:** Radial Velocities of Sequence E Stars. Stars are identified by their MACHO numbers.

| HJD       | 77.7429.189 | 77.7548.68 | 77.7672.98 | 77.7673.79 |
|-----------|-------------|------------|------------|------------|
| 2954.8508 | 0.00        | 247.1836   | 270.6885   | 265.7394   |
| 3005.8604 | 0.00        | 242.5239   | 260.0903   | 258.5819   |
| 3067.6028 | 0.00        | 237.8895   | 225.7872   | 239.5893   |
| 3091.5571 | 0.00        | 238.4238   | 251.1337   | 265.9271   |
| 3280.8611 | 272.6101    | 255.7782   | 284.0382   | 244.0299   |

variations of such stars are dominated by the orbital motion, but light variability is caused mainly by the change in apparent surface area as the star orbits around its companion. Because of this, the light curve of an ellipsoidal variable shows two maxima and minima per orbit – two cycles for every one cycle of the velocity curve. This is an easy way to unambiguously identify ellipsoidal variables and we use this test here.

Four of the other sequences of LPVs – A, B, C' and C – are known to harbour radially pulsating variables (Wood et al., 1999). A fifth sequence, sequence D, contains stars which show Long Secondary Periods. The origin of Long Secondary Periods (LSPs) remains something of a mystery, though several attempts have been made to discover it (Wood et al., 1999; Hinkle et al., 2002; Olivier & Wood, 2003; Wood et al., 2004; Derekas et al., 2006; Nicholls et al., 2009). Due to their overlap in the period–luminosity diagram, some authors (Soszyński et al., 2004b; Soszyński, 2007) have suggested that stars on sequences D and E may be fundamentally the same – binaries showing ellipsoidal variability.

Here we study a sample of sequence E binaries. In particular, we present new radial velocity data derived from VLT spectra, which we use alongside MACHO light curves. We show that the variations of stars on sequences D and E are caused by different mechanisms. Preliminary results for three stars are given in Adams et al. (2006).

## 4.2 Observations and Data Reduction

The observations and data reduction for this sample are the same as for our recently published sequence D sample (Nicholls et al., 2009). The spectra were taken using the FLAMES/ GIRAFFE spectrograph (Pasquini et al., 2002) on the European Southern Observatory's Very Large Telescope (VLT), on 21 nights from 2003 November to 2006 March. Radial velocities were calculated via cross-correlation with the IRAF task *fxcor*. The reader is referred to Nicholls et al. (2009) for details. Table 4.1 shows the radial velocities calculated for part of our sample for a few dates. The full table, with radial velocities of our whole sample for all dates, is available online or in Appendix E.

### 4.3 Results

Plots of phased light and velocity variations for all the stars in our sequence E sample are shown in Figures 4.1 and 4.2. A clear doubling of the phased light curve with respect to the phased velocity curve can be seen for all stars in our sample. This behaviour unambiguously demonstrates that these stars are ellipsoidal variables. Many of the stars show lightcurves with equal maxima and unequal minima, which suggests that one end of the ellipsoid is hotter and brighter than the other. From Figures 4.1 and 4.2 we see that the deepest minimum occurs at mean velocity during decreasing radial velocity, i.e. when the red giant is behind its companion. Therefore the inner end of the red giant ellipsoid – the end closest to the companion – is the cooler end, and the side furthest from the companion is hotter. This is most likely due to gravity darkening towards the companion.

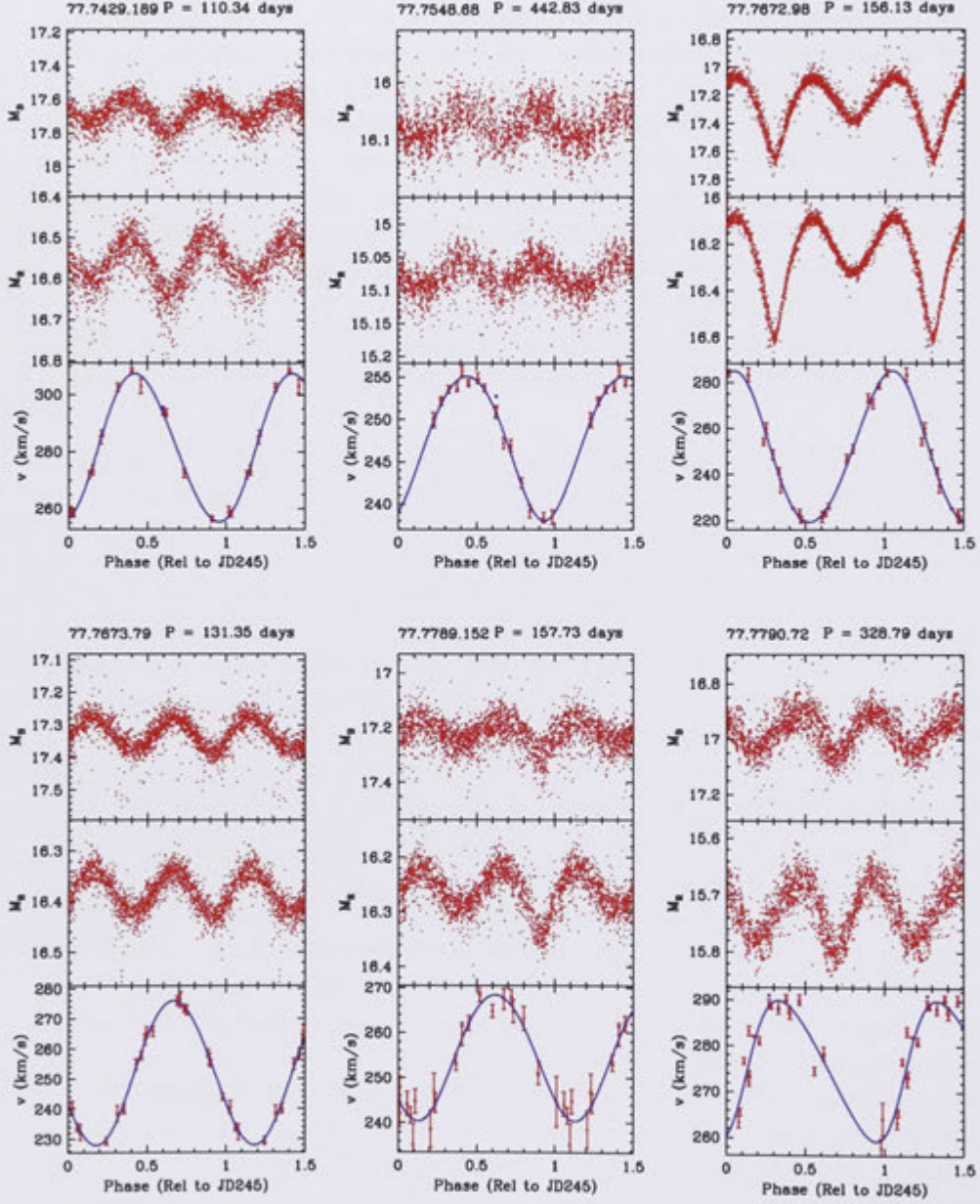
A histogram of the velocity amplitudes of our sample is shown in Figure 4.3. The majority of values lie between 15 and 55 km s<sup>-1</sup>, and the mean velocity amplitude is 43.3 km s<sup>-1</sup>.

We have made a binary fit to the velocity curves of our sequence E red giants (see Section 2.5 of Nicholls et al., 2009). We calculated the mass function,

$$f(m) = \frac{K^3 P}{2\pi G} = \frac{m^3 \sin^3 i}{(m + M)^2}, \quad (4.1)$$

using the observed values for period ( $P$ ) and velocity semiamplitude ( $K$ ) (Table 4.2). Using the calculated mass function of our binary fit and assuming a total system mass of  $2 M_\odot$ , we calculated an estimated companion mass for each of the stars in our sample. As expected, for most systems the companion is less massive than the red giant, but for two stars this resulted in companions with significantly higher mass than the red giant. This is unlikely since the more massive companion should evolve to the red giant stage first, and even if the current red giant was originally the less massive star, its companion would most likely now be a white dwarf of lower mass than the red giant. In these two cases we chose the total mass to be such that the red giant and its companion had equal mass. This results in higher masses for these stars (total system masses of  $\sim 4.5 M_\odot$ .) The mass estimates are shown in Table 4.2, alongside the other parameters of the binary fit to the velocity. Here  $\gamma$  is the system velocity,  $e$  is the eccentricity,  $\omega$  is the angle of periastron,  $T$  is the date of periastron,  $a \sin i$  is the semimajor axis of the red giant's orbit,  $f(m)$  is the mass function,  $M$  is the mass of the red giant, and  $m$  the mass of its companion. We assume  $\sin i = 1$  when calculating the masses. The errors for each element are shown on the line below each star.

The eccentricity of a binary system is expected to decrease over time due to circularising tidal forces (Zahn, 1977), provided no mechanism is in place that will stabilise or increase the orbital eccentricity. Thus binaries with one or more red giant components are expected to describe relatively circular orbits. We confirmed this theory by calculating the circularisation time for our stars, using the formula given in Soker (2000). The median circularisation time of our sample is only  $\sim 3500$  yr.



**Figure 4.1:** Phased MACHO blue ( $M_B$ ) and red ( $M_R$ ) light curves and phased radial velocity curves for our sequence E stars. The blue line shows the binary fit to the velocity curve.

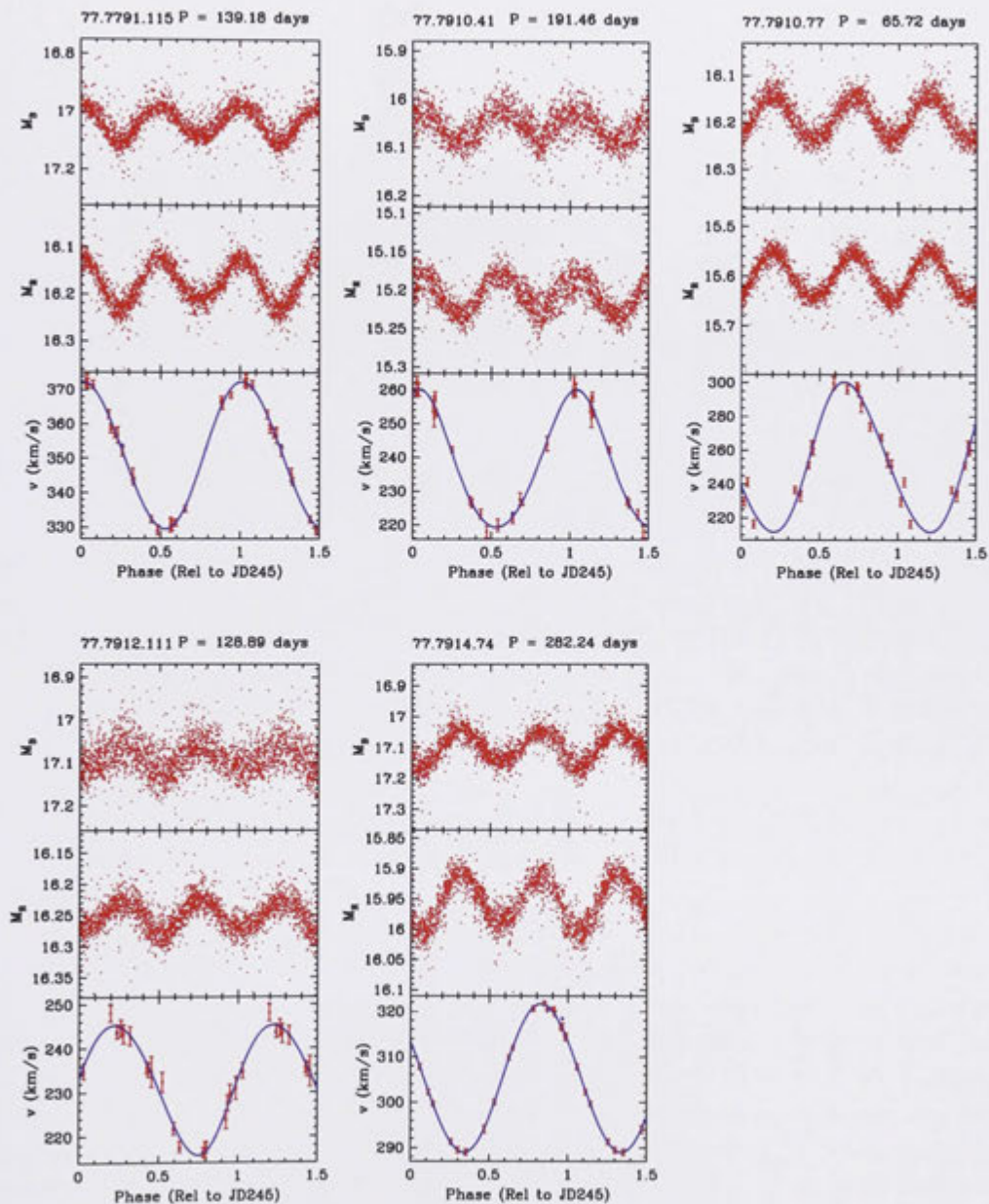


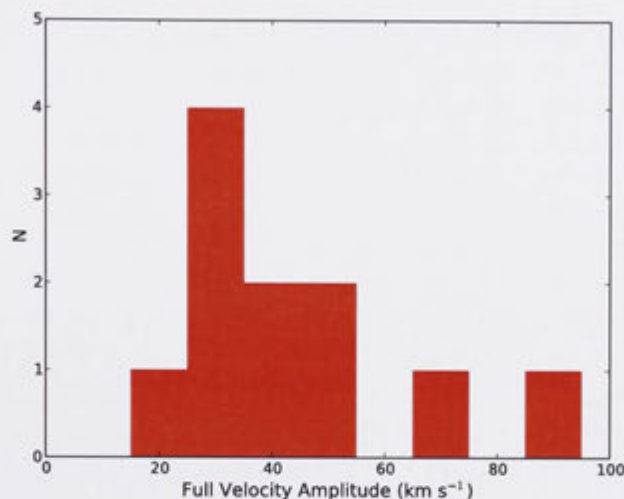
Figure 4.2: Same as Figure 4.1.



**Table 4.2:** Orbital Elements for Sequence E Stars

| Star        | $\gamma$<br>(km s <sup>-1</sup> ) | $K$<br>(km s <sup>-1</sup> ) | $e$            | $\omega$<br>(deg) | $T$<br>(HJD)     | $P$<br>(days) | $a \sin i$<br>(R <sub>⊙</sub> ) | $f(m)$<br>(M <sub>⊙</sub> ) | $M^a$<br>(M <sub>⊙</sub> ) | $m$<br>(M <sub>⊙</sub> ) |
|-------------|-----------------------------------|------------------------------|----------------|-------------------|------------------|---------------|---------------------------------|-----------------------------|----------------------------|--------------------------|
| 77.7429.189 | 281.40<br>± 0.57                  | 25.99<br>± 0.80              | 0.05<br>± 0.03 | 275.38<br>± 28.52 | 3332.5<br>± 8.8  | 110.34        | 56.58<br>± 1.75                 | 0.2003<br>± 0.0186          | 1.07                       | 0.93                     |
| 77.7548.68  | 247.20<br>± 0.19                  | 8.54<br>± 0.24               | 0.07<br>± 0.03 | 170.67<br>± 25.63 | 3502.6<br>± 32.9 | 442.83        | 74.55<br>± 2.22                 | 0.0285<br>± 0.0024          | 1.52                       | 0.48                     |
| 77.7672.98  | 250.71<br>± 0.75                  | 32.77<br>± 1.10              | 0.06<br>± 0.03 | 38.99<br>± 29.11  | 2989.4<br>± 12.3 | 156.13        | 100.92<br>± 3.42                | 0.5679<br>± 0.0575          | 2.27                       | 2.27                     |
| 77.7673.79  | 252.37<br>± 0.41                  | 24.01<br>± 0.59              | 0.02<br>± 0.02 | 236.49<br>± 61.77 | 3064.4<br>± 22.6 | 131.35        | 62.30<br>± 1.55                 | 0.1887<br>± 0.0140          | 1.09                       | 0.91                     |
| 77.7789.152 | 255.04<br>± 0.74                  | 14.03<br>± 0.97              | 0.05<br>± 0.08 | 198.55<br>± 90.81 | 3024.2<br>± 40.5 | 157.73        | 43.67<br>± 3.05                 | 0.0451<br>± 0.0094          | 1.44                       | 0.56                     |
| 77.7790.72  | 275.00<br>± 0.83                  | 15.35<br>± 0.92              | 0.19<br>± 0.06 | 262.20<br>± 13.11 | 3326.7<br>± 10.2 | 328.79        | 97.85<br>± 6.02                 | 0.1167<br>± 0.0214          | 1.22                       | 0.78                     |
| 77.7791.115 | 350.88<br>± 0.30                  | 21.47<br>± 0.35              | 0.03<br>± 0.02 | 275.04<br>± 40.51 | 3032.0<br>± 16.3 | 139.18        | 59.02<br>± 0.97                 | 0.1429<br>± 0.0070          | 1.17                       | 0.83                     |
| 77.7910.41  | 238.06<br>± 0.55                  | 20.41<br>± 0.66              | 0.08<br>± 0.04 | 10.03<br>± 21.82  | 3075.8<br>± 11.8 | 191.46        | 76.94<br>± 2.53                 | 0.1673<br>± 0.0163          | 1.13                       | 0.87                     |
| 77.7910.77  | 255.34<br>± 1.67                  | 44.35<br>± 2.83              | 0.08<br>± 0.04 | 279.65<br>± 38.55 | 2987.6<br>± 7.1  | 65.72         | 57.38<br>± 3.67                 | 0.5890<br>± 0.1131          | 2.36                       | 2.36                     |
| 77.7912.111 | 231.16<br>± 0.45                  | 14.76<br>± 0.62              | 0.06<br>± 0.04 | 223.73<br>± 41.73 | 3075.1<br>± 14.7 | 128.89        | 37.50<br>± 1.57                 | 0.0428<br>± 0.0054          | 1.44                       | 0.56                     |
| 77.7914.74  | 305.31<br>± 0.11                  | 16.33<br>± 0.14              | 0.02<br>± 0.01 | 272.80<br>± 24.26 | 3271.8<br>± 18.9 | 282.24        | 91.04<br>± 0.79                 | 0.1276<br>± 0.0033          | 1.20                       | 0.80                     |

<sup>a</sup>Here we assume  $\sin i = 1$ .



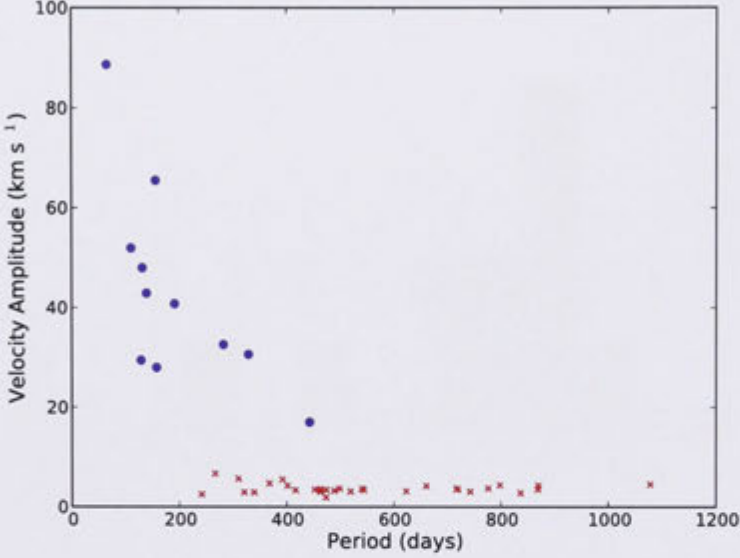
**Figure 4.3:** A histogram of the velocity amplitude for our sample.

For comparison, the time a  $1 M_{\odot}$ ,  $Z = 0.008$  red giant takes to double its radius when  $R \sim 30 R_{\odot}$  is  $\sim 2 \times 10^7$  yr (using the evolutionary tracks of Girardi et al., 2000). The value of  $30 R_{\odot}$  was chosen as a typical Roche Lobe radius for these stars (see the velocity amplitude calculations given later in this Section). A doubling of the radius is an estimate of the evolution time over which the tides have had time to act. Ten of the eleven stars in our sample have  $e < 0.1$ , and the mean eccentricity of the sample is 0.07. Therefore the majority of our sample of red giant binaries have fairly circular orbits, as expected. However some sequence E stars do show confoundingly high eccentricities (see Soszyński et al., 2004b), and this is a problem that must be solved in the future.

The relation between velocity amplitude and period for our sample and for the sequence D sample of Nicholls et al. (2009) is plotted in Figure 4.4. In a binary system, for given masses, a longer period means a wider orbit, and thus a smaller amplitude in velocity variation. Figure 4.4 shows velocity amplitude decreases with increasing period for the sequence E stars, as expected. However the sequence D stars show the same velocity amplitudes for all periods and do not follow the expected binary relation. A vivid demonstration of the disparity between these two samples is found in the region where their periods overlap. At periods between 200 and 450 days, the difference in velocity amplitude between the sequence D and sequence E samples is as much as  $30 \text{ km s}^{-1}$ .

Ellipsoidal variability is only visible once a star has substantially filled its Roche Lobe. Stars in wider orbits (with lower velocity amplitudes) will fill their Roche Lobes when they are further up the giant branch, and thus will be more luminous than stars in closer orbits. For a given luminosity (and radius) there is a range of velocity amplitudes the star may have, the maximum of which is dictated by





**Figure 4.4:** Full velocity amplitude plotted against orbital period for our sequence E sample (blue points) and the sequence D sample of Nicholls et al. (2009) (red crosses).

the size of the closest possible orbit the companion can occupy. Therefore, for our ellipsoidal variables we expect that the maximum velocity amplitude should decrease with increasing luminosity, but that stars may occupy velocity amplitudes below the maximum for a given luminosity. This is shown in Figure 4.5 which gives a plot of  $K$  magnitude against velocity amplitude for our sequence E stars. In order to define the upper limit of velocity amplitude for a given luminosity, we calculated the minimum orbital separation for a theoretical sample of binaries with equal mass components (mass ratios of  $q = 1$ ) in which the red giant is filling its Roche Lobe. Using the approximation given in Eggleton (1983), we calculated the Roche Lobe radius  $r_L$  to be 0.37, in units of orbital separation. Therefore the minimum orbital separation for a Roche-Lobe filling binary with  $q = 1$  is  $a = \frac{r_L}{0.37} = 2.7r_L$ . We substitute for  $r_L$  the radius expected for a given luminosity in these stars, calculated from a fit made to the radius- $K$  magnitude data for our sample. Finally we calculated the maximum velocity amplitude assuming a circular orbit and components of mass  $1 M_\odot$ . This velocity amplitude upper limit is shown by the solid blue line in Figure 4.5.

Most stars lie where expected in Figure 4.5 but two stars lie above the upper limit line. These are the two systems with higher mass components, mentioned earlier. As both these systems have components of around  $2.3 M_\odot$ , we also calculated the maximum velocity amplitude for stars of this mass, and this is shown by the green dashed line in Figure 4.5. One star lies above this limit. It appears somewhat atypical, as it has a significantly higher effective temperature than the rest of the sample ( $\sim 5200$  K compared to the median 4200 K) and hence a smaller radius. It

**Table 4.3:** Sequence E Star Properties

| Star        | $R$<br>( $R_{\odot}$ ) | $L$<br>( $L_{\odot}$ ) | $T_{\text{eff}}$<br>(K) | $a$<br>( $R_{\odot}$ ) |
|-------------|------------------------|------------------------|-------------------------|------------------------|
| 77.7429.189 | 48.92                  | 593.16                 | 4071.43                 | 121.83                 |
| 77.7548.68  | 92.03                  | 1917.72                | 3980.39                 | 307.67                 |
| 77.7672.98  | 56.13                  | 869.34                 | 4181.83                 | 201.84                 |
| 77.7673.79  | 42.24                  | 591.59                 | 4378.57                 | 136.84                 |
| 77.7789.152 | 52.85                  | 841.10                 | 4274.26                 | 154.60                 |
| 77.7790.72  | 92.71                  | 1736.69                | 3868.59                 | 252.27                 |
| 77.7791.115 | 49.66                  | 805.48                 | 4362.15                 | 142.23                 |
| 77.7910.41  | 72.37                  | 1790.14                | 4412.02                 | 175.91                 |
| 77.7910.77  | 38.58                  | 983.43                 | 5202.34                 | 114.76                 |
| 77.7912.111 | 47.41                  | 604.76                 | 4155.77                 | 135.12                 |
| 77.7914.74  | 70.70                  | 1079.15                | 3933.14                 | 227.86                 |

therefore does not overflow its Roche Lobe as Figure 4.5 suggests.

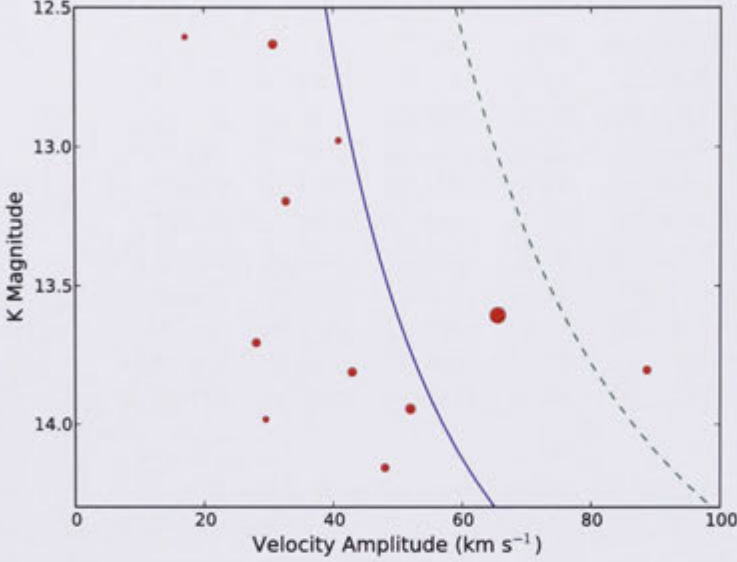
Table 4.3 gives the radius, luminosity, effective temperature and orbital separation data for our sample. For the majority of stars, these properties were calculated using the 2MASS  $J$  and  $K$  magnitudes. However for the star 77.7910.77, which lies outside the green dashed limit in Figure 4.5, the properties were calculated from OGLE  $V - I$  values, which are more reliable for warmer stars. Due to this star's warmer temperature, we suspect it could be a helium core burning clump star or a blue loop star.

#### 4.3.1 The Mid-Infrared Colour of Sequence E Stars

It has recently been shown (Wood & Nicholls, 2009) that variable red giants belonging to sequence D have a mid-infrared excess when compared to similar red giants without the Long Secondary Period that characterises sequence D stars. This mid-infrared excess is assumed to arise from circumstellar dust associated with the presence of the LSP. Since the sequence E stars are close binary systems, some of which have quite eccentric orbits (Soszyński et al., 2004b), there is a possibility that these systems could have substantial circumstellar disks of dust and gas.

In order to investigate this possibility, we searched for a mid-infrared excess in sequence E stars in the LMC using mid-infrared data from the Spitzer Space Telescope SAGE survey (Blum et al., 2006; Meixner et al., 2006). The sequence E stars were obtained from the catalogue given by Fraser et al. (2008). None of these objects were detected at  $24\mu\text{m}$  in the SAGE survey but 262 were detected at  $8\mu\text{m}$ . The light curves of these 262 stars were examined and it was found that only 184 could be considered as definite sequence E stars, i.e. ellipsoidal or eclipsing binary systems. The remainder were variables whose light curve characteristics showed that they belonged to sequence D or the pulsation sequences 1 to 4 (using the notation in Fraser et al., 2008) or they were stars of indeterminate light curve type.

In order to see if the sequence E stars show a mid-infrared excess, we obtained a comparator sample of stars that were similar to the sequence E stars, but without



**Figure 4.5:**  $K$  magnitude (from 2MASS) plotted against velocity amplitude for our sequence E stars. The point size shows relative light amplitude in MACHO red. The solid blue curve gives the upper velocity limit for equal-mass components of  $1 M_{\odot}$ , and the dashed green curve gives the upper limit for equal-mass components of  $2.3 M_{\odot}$ . See text for details.

binary companions. Such stars are the normal, non-varying field red giants in the LMC. Since the sequence E stars that were detected at  $8 \mu\text{m}$  have  $12.5 < K < 14$  and  $0.6 < J - K < 1.4$ , we selected comparison sources from the SAGE survey with these characteristics along with the requirement of an  $8 \mu\text{m}$  detection. An examination of this sample of  $\sim 40000$  objects showed that sources fainter than  $K = 13.5$  were near the  $8 \mu\text{m}$  faint detection limit and that this significantly biased the population of detected stars in favour of objects with a higher  $K - [8]$  colour. We therefore omitted such stars and we compared sequence E stars and non-varying field red giants only in the interval  $12.5 < K < 13.5$ . Finally, all variable stars in the catalogue of Fraser et al. (2008) were removed from the list of comparison sources. This left 144 sequence E stars and  $\sim 33000$  non-varying field red giants. The  $K - [8]$  colour distributions of these two samples were then examined to search for an  $8 \mu\text{m}$  mid-infrared excess. A two sample K-S test gives a probability of up to 0.89 that the sequence E stars and non-varying field red giants come from the same underlying distribution in  $K - [8]$  colour. In other words, there is no evidence that sequence E variability generally leads to a significant amount of circumstellar dust and a mid-infrared excess.

## 4.4 Discussion and Conclusions

With new velocity curves, we now have strong evidence that the sequence E variation is indeed caused by ellipsoidal variability. This is shown by the doubling of the light curve with respect to the velocity curve in these stars, as in Figures 4.1 and 4.2.

However, as we showed in Nicholls et al. (2009), the phased light curves of sequence D variables – the stars with Long Secondary Periods – do not show this doubling phenomenon (see fig. 3 of that paper). Although it has been suggested that the sequence D and E variations may have a common origin due to their proximity in the period–luminosity plane (Soszyński et al., 2004b), and the possible existence of ellipsoidal shapes in their residual light curves (Soszyński, 2007), no sequence D star has so far been found whose light executes two cycles during one velocity cycle. This seems to rule out ellipsoidal variation in sequence D stars.

A further difference between the stars on sequences D and E is demonstrated by their respective velocity amplitudes. The sequence E stars of the current sample show full velocity amplitudes of at least  $15 \text{ km s}^{-1}$  – some much larger – as can be seen in Figure 4.3. However as we showed in Nicholls et al. (2009), stars with LSPs have much smaller velocity amplitudes, typically around  $3.5 \text{ km s}^{-1}$ . This marked difference in the size of the velocity variations between sequence D and E – which can be seen in Figure 4.4 – supports our assertion that they are caused by different mechanisms.

The sequence E stars, known binaries, show an expected spread in companion mass estimates. However this distribution seems very different for the sequence D stars. If treated as binaries, sequence D stars have companions that are small and absurdly similar ( $\sim 0.09 M_{\odot}$ ). Additionally, the angles of periastron of sequence D stars are heavily biased towards large values, whereas we would expect a uniform distribution for binaries. Unfortunately we cannot compare the distribution of angle of periastron for the current sequence E sample: as most of these stars have almost circular orbits, angle of periastron is poorly defined (see the large errors in Table 4.2).

The distribution of eccentricity is very different for sequence E and D stars, when the latter are treated as binaries. Most of the red giant binaries on sequence E have low-eccentricity orbits, as expected for their evolutionary state. However Nicholls et al. (2009) showed that the sequence D stars have a significantly higher eccentricity, if we assume they are binaries (the mean eccentricity of that sample is 0.3). A two-sample K–S test gives a probability of less than  $2.1 \times 10^{-6}$  that the sequence D and E eccentricity distributions come from the same underlying distribution.

Further evidence that sequence D stars are not ellipsoidal variables is given by the relation between luminosity and velocity amplitude in those stars. In Figure 4.5, we showed that the sequence E stars generally populate an area delineated by a maximum velocity amplitude–luminosity relation, as expected for ellipsoidal variables. However, Nicholls et al. (2009) showed that the sequence D stars do not show any correlation between these properties.

Finally, we have searched for a mid-infrared excess in sequence E stars since such an excess was found among the sequence D stars. No mid-infrared excess was found, demonstrating another difference from the sequence D stars.



In summary, we have demonstrated several significant differences between stars on sequences D and E. Most particularly, we have shown that Long Secondary Periods – the sequence D variation – are not caused by ellipsoidal variability, unlike the variation of the sequence E stars. The cause of Long Secondary Periods remains, at this time, a mystery.

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# Eccentric Ellipsoidal Red Giant Binaries in the LMC: Complete Orbital Solutions and Comments on Interaction at Periastron

C. P. Nicholls and P. R. Wood, in preparation

## Abstract

Modelling ellipsoidal variables with known distances can lead to exact determination of the masses of both components, even in the absence of eclipses. We present such modelling using light and radial velocity curves of ellipsoidal red giant binaries in the LMC, where they are also known as sequence E stars. Stars were selected as likely eccentric systems on the basis of light curve shape alone. We have confirmed their eccentric nature and obtained system parameters using the Wilson–Devinney code.

Most stars in our sample exhibit unequal light maxima as well as minima, a phenomenon not observed in sequence E variables with circular orbits. We find evidence that the shape of the red giant changes throughout the orbit due to the high eccentricity and the varying influence of the companion.

Defining the parameters of these systems paves the way for modelling to determine by what mechanism eccentricity is maintained in evolved binaries.

## 5.1 Introduction

Long period variables (LPVs) occupy several sequences in the period–luminosity plane (Wood et al., 1999; Soszyński et al., 2004a; Ita et al., 2004; Fraser et al., 2005; Soszyński et al., 2007; Fraser et al., 2008). Most of these sequences represent radially pulsating stars on the red giant branch (RGB) or asymptotic giant branch (AGB), with different sequences corresponding to different modes of pulsation. There are two exceptions. Sequence D, lying at the longest periods, is occupied by AGB stars showing two concurrent forms of variation; these stars are also known as Long

Secondary Period Variables, or LSPVs (Wood et al. 1999; Hinkle et al., 2002; Wood et al., 2004; Nicholls et al., 2009; Wood & Nicholls, 2009). The other sequence lies close to sequence D and extends to the lowest luminosities. It was labelled by Wood et al. (1999) with the letter E and was shown to consist of red giant binaries. Soszyński et al. (2004b) identified the light variation as due to ellipsoidal variations, as alternate minima often have different depths. Sequence E stars exhibit regular light variations with periods between  $\sim 50$  and 1000 days and amplitudes  $\lesssim 0.3$  mag in the MACHO red band. They lie on both the RGB and the AGB.

Ellipsoidal variability is observed in close binaries, where the Roche Lobe of a star is distorted by the gravitational influence of its companion. When the primary star evolves and begins to fill its Roche Lobe, it takes on an elongated, or ‘ellipsoidal’ shape. Rotation of the star’s aspherical shape causes variation in the light curve, even in the absence of eclipses.

The hallmark of ellipsoidal variables is the relationship between the phased light and radial velocity curves. The radial velocity of the system is dominated by the orbital motion, but the light variability is mainly due to the change in apparent surface area of the distorted primary as it orbits its companion. Light maxima occur when the ellipsoidal star has one of its broad sides facing the observer and minima correspond to those times when the star is ‘end-on’ from the observer’s point of view. This orientation-induced light variability of the ellipsoidal star means the system’s light curve displays two maxima and minima every orbit; the phased light curve shows two cycles for every cycle of the phased velocity curve.

Stars on sequence E were first unambiguously demonstrated to be ellipsoidal variables by Nicholls et al. (2010). In that paper we presented phased light and velocity curves of 11 sequence E binaries in the LMC, each showing doubling of the velocity period with respect to the light period (see figs. 1 and 2 of that paper). It is expected that the current red giant is the more massive star and the first to evolve, and that the less massive companion is normally on the main sequence (MS) and does not contribute significantly to the detected flux.

A subset of the sequence E ellipsoidal red giant binaries was suggested by Soszyński et al. (2004b) to have eccentric orbits, based on their unusual light curve shapes. Eccentric orbits in close binaries with evolved components are unexpected, as tidal theory predicts that orbits should quickly circularise once stars begin to evolve (Zahn, 1977). As an example, in Nicholls et al. (2010) we calculated the circularisation time for sequence E stars using the formula given in Soker (2000). We found the typical circularisation time for sequence E binaries to be  $\sim 3500$  yr, much shorter than the lifetime of the ellipsoidal phase which is  $\sim 0.8$  Myr (Nie et al., 2011, in preparation). Eccentric orbits in evolved close binaries are thought to imply the presence of some mechanism that can maintain or increase eccentricity, opposing the tidal forces.

A number of other evolved binaries are also known to have unexpectedly eccentric orbits. These include post-AGB binaries (van Winckel, 2003) and Barium stars (Izzard et al., 2010). It is unclear why significantly nonzero orbital eccentricity is present in any of these systems, but several mechanisms have been suggested. These include mass transfer at periastron (Soker, 2000) and tidal interaction with a

circumbinary disk (Artymowicz et al., 1991).

The evolution of close binaries like ellipsoidal variables may end in a number of different ways, depending on the initial orbital separation and subsequent binary evolution. All observable ellipsoidal variables are partially filling their Roche Lobes. If the Roche Lobe is filled below the RGB tip, it is likely the binary will undergo a common envelope (CE) event and evolve dynamically to an effective temperature that is determined by the amount of mass left on the red giant core. If this  $T_{\text{eff}}$  is significantly less than  $3 \times 10^4$  K, the ejected stellar envelope may not be ionised before it disperses, due to the slow evolution rate resulting from lower luminosity. If an ellipsoidal variable ends its evolution via the superwind at the AGB tip without filling its Roche Lobe, as single AGB stars do, it will produce a planetary nebula (PN) with a wide binary companion. Variables that fill their Roche Lobes somewhere on the AGB should undergo a CE event and become close binary PN. Further comment on the relationship of ellipsoidal variables to binary PN and asymmetric PN can be found in Nicholls & Wood (2011).

In this paper we analyse a sample of LMC sequence E binaries which display light curve shapes that Soszyński et al. (2004b) linked with eccentric orbits. We aim to confirm their eccentric nature and describe the components of each binary and their orbits, including estimates of absolute masses as is possible for ellipsoidal variables with known distances (e.g. Wilson et al., 2009). The results provide input for future studies on the likelihood or otherwise of proposed mechanisms for maintaining eccentricity. We use radial velocity curves obtained from observations taken with the ANU 2.3 m telescope at Siding Spring Observatory (SSO) and OGLE II light curves. Modelling of the light and velocity curves is done with the 2010 version of the Wilson–Devinney code (Wilson & Devinney, 1971).

## 5.2 Observations and Data Reduction

We selected a sample of seven sequence E stars with *I*-band magnitude brighter than 16 and light curves indicative of eccentric orbits from the OGLE II database. Table 5.1 gives the OGLE identification, right ascension, declination, and mean *I* magnitude of each star. The stars were monitored using the Double Beam Spectrograph (DBS, Rodgers et al., 1988) at the ANU 2.3 m telescope at SSO from May 2006 to April 2008, with the aim of obtaining radial velocities.

Our study used only the red arm of the DBS with a grating of 1200 lines/mm, a two-pixel resolution of  $0.96 \text{ \AA}$  and a grating angle of  $32^\circ 4'$ , giving a wavelength range of approximately 8000 – 9000  $\text{\AA}$ . This gave spectra centred on the Ca triplet, ideal for cross-correlation and the calculation of radial velocities. A Ne–Ar arc and an internal flat were taken after each exposure for calibration and to eliminate strong fringing on the CCDs. The spectra were taken over 15 runs throughout the monitoring period with 34 nights total observing.

Data reduction was done in IRAF. The spectra had the overscan bias subtracted and the overscan region removed from the images, and then the object and arc spectra were flatfielded and the spectra extracted using the *apextract* package. The



**Table 5.1:** Candidate eccentric ellipsoidal variables in the OGLE II database.

| OGLE ID                | RA          | Dec         | <i>I</i> |
|------------------------|-------------|-------------|----------|
| OGLE052013.51-692253.2 | 05:20:13.51 | -69:22:53.2 | 15.17    |
| OGLE052438.40-700028.8 | 05:24:38.40 | -70:00:28.8 | 13.66    |
| OGLE052812.41-693417.9 | 05:28:12.41 | -69:34:17.9 | 15.78    |
| OGLE052850.12-701211.2 | 05:28:50.12 | -70:12:11.2 | 13.80    |
| OGLE053033.55-701742.0 | 05:30:33.55 | -70:17:42.0 | 13.87    |
| OGLE053124.49-701927.4 | 05:31:24.49 | -70:19:27.4 | 14.96    |
| OGLE053159.96-693439.5 | 05:31:59.96 | -69:34:39.5 | 14.29    |

arcs were used to wavelength calibrate the object spectra, obvious cosmic rays were removed, and stars with multiple spectra taken on a single night were added using *scombine*. Each star has between 13 and 17 spectra spread over the monitoring period.

Radial velocities were calculated using IRAF's cross-correlation task, *fxcor*. A single spectrum with high signal to noise and narrow lines was selected from each star's collection to act as a template for that star's cross-correlation. Absolute radial velocities were provided by cross-correlation of the template with the radial velocity standard star  $\alpha$  Cet, whose spectrum was taken on 11th November 2006 with the above observing configuration. Cross-correlation was done in the wavelength region 8370 – 8920 Å, which was mostly free of telluric lines and included the Ca triplet. Spectra were then cross-correlated to a telluric spectrum in the region 8120 – 8370 Å (covering the bulk of the telluric lines) to check for zero point offsets in the reduction procedure. No zero point errors were found.

The OGLE *I*-band light curves and our new velocity curves of all 7 stars in the sample can be seen in Figures 5.1 – 5.7. The Heliocentric Julian Dates (HJD) of the observations and the calculated radial velocities are shown in Table 5.2. Typical velocity errors are of the order of  $2.5 \text{ km s}^{-1}$  and are represented by the error bars in Figures 5.1 – 5.7.

### 5.3 Absolute Solutions of Orbital and Stellar Parameters

Modelling of the light and velocity curves is done with the 2010 version of the Wilson–Devinney code (Wilson & Devinney, 1971). Analysing both the light and velocity curves of ellipsoidal variables at known distances provides a unique opportunity to determine complete binary solutions, even in the absence of eclipses. Implementation of this within the Wilson–Devinney (WD) code is known as Inverse Distance Estimation (IDE) (Wilson et al., 2009). From a conceptual perspective, the basic method is as follows. If the distance, observed magnitude and extinction are known, the absolute luminosity of an ellipsoidal variable can be derived. If the temperature is also known (e.g. from spectra or colour), the stellar radius can be calculated.

**Table 5.2:** Radial velocities in  $\text{kms}^{-1}$  of eccentric sequence E stars. Stars are identified by their OGLE RA.

| HJD        | 052013.51 | 052438.40 | 052812.41 | 052850.12 | 053033.55 | 053124.49 | 053159.96 |
|------------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| 2453872.91 | 254.76    | 296.16    | -         | 251.91    | 259.75    | -         | -         |
| 2453981.20 | 253.11    | 283.78    | -         | 238.42    | 237.13    | -         | -         |
| 2453982.23 | -         | -         | -         | -         | -         | 248.22    | 232.90    |
| 2453983.23 | -         | -         | 261.03    | -         | -         | 246.62    | -         |
| 2454050.17 | 244.62    | 262.61    | -         | 228.23    | 231.69    | 253.12    | -         |
| 2454051.10 | -         | -         | 239.52    | -         | -         | 251.42    | 227.26    |
| 2454109.16 | -         | 245.09    | -         | 221.65    | 244.45    | -         | -         |
| 2454110.04 | 231.78    | -         | -         | -         | -         | -         | 232.08    |
| 2454111.13 | -         | -         | 249.70    | -         | -         | 246.83    | -         |
| 2454136.22 | -         | 245.40    | -         | 227.83    | 257.28    | -         | -         |
| 2454137.17 | 228.82    | -         | -         | -         | -         | 244.42    | 240.39    |
| 2454137.99 | -         | -         | 255.28    | -         | -         | -         | -         |
| 2454167.14 | -         | 253.05    | -         | -         | -         | -         | -         |
| 2454167.98 | 239.62    | 247.33    | -         | 232.92    | 268.22    | -         | 254.69    |
| 2454168.93 | -         | -         | 266.21    | -         | -         | 249.55    | -         |
| 2454206.89 | 243.56    | 265.81    | 263.00    | 241.77    | 271.55    | 250.76    | -         |
| 2454207.95 | -         | -         | -         | -         | -         | -         | 255.71    |
| 2454310.25 | 261.01    | 297.26    | -         | 254.92    | 249.89    | -         | 250.59    |
| 2454347.23 | -         | -         | -         | 256.96    | 243.51    | 222.24    | 247.46    |
| 2454348.31 | 253.91    | 294.11    | -         | -         | -         | -         | -         |
| 2454349.10 | -         | -         | -         | -         | -         | -         | -         |
| 2454378.17 | 261.02    | 288.66    | 260.25    | 257.33    | 237.30    | 230.38    | 243.08    |
| 2454409.16 | 261.11    | 276.56    | -         | 256.44    | 235.05    | 238.04    | 241.15    |
| 2454452.23 | -         | 265.40    | -         | 256.67    | 235.23    | 247.99    | 233.66    |
| 2454453.95 | -         | -         | 275.04    | -         | -         | -         | -         |
| 2454454.10 | -         | -         | 267.86    | -         | -         | -         | -         |
| 2454524.07 | -         | 243.97    | -         | -         | -         | -         | -         |
| 2454543.10 | 241.48    | 242.95    | -         | 250.30    | 264.18    | 255.56    | 228.90    |
| 2454543.94 | -         | -         | 245.65    | -         | -         | -         | -         |
| 2454545.09 | 234.34    | -         | 247.01    | -         | -         | 253.69    | 231.90    |
| 2454571.07 | 215.03    | 244.55    | -         | 248.54    | 270.34    | 261.19    | 228.57    |
| 2454571.87 | 223.48    | -         | 236.37    | -         | -         | -         | -         |
| 2454573.00 | 221.59    | 245.22    | -         | 249.44    | -         | -         | -         |

If the orbital inclination of an ellipsoidal variable is known or can be constrained, then the amplitude of the light variation measures what fraction of its Roche Lobe the ellipsoidal star fills. The previously calculated radius therefore gives the size of the Roche Lobe,  $R_{\text{lobe}}$ . The radial velocity curve provides the semimajor axis of the red giant's orbit,  $a_1$ , so a solution for mass ratio  $q$  is possible, since  $q$  is a function of  $R_{\text{lobe}}/a_1$ . So for an assumed  $i$ , the absolute masses of stars, as opposed to the  $m \sin i$ , are produced. Therefore we need step only the inclination in our solutions to find the best fit to the light and velocity curves.

Our analysis of ellipsoidal red giant binaries with undetectable companions and known distances has been preceded by analysis of a similar binary by Wilson et al. (2009), who also pioneered the method described above and conveniently added this capability to the 2010 version of the WD code. The reader is referred to that paper for a more in-depth explanation of absolute light and velocity analysis of ellipsoidal variables.

### 5.3.1 Modelling the Light and Velocity Curves

To describe our ellipsoidal variables and obtain their orbital parameters, we used the 2010 version of the WD code (Wilson & Devinney, 1971; Wilson, 2008; Wilson et al., 2009). Preliminary fits to the velocity curves were made with a Fortran program, FITALL, to obtain starting estimates of input parameters for the WD modelling. This allowed us to fix the system velocity  $v_\gamma$ , and gave starting estimates for the semimajor axis  $a$ , angle of periastron  $\omega$ , eccentricity  $e$ , and mass ratio  $q$ .

The luminosity of each star was calculated using its median OGLE  $V - I$  colour, a bolometric correction to  $I$  calculated from the Houdashelt et al. (2000) models for K and M giants, the LMC distance modulus 18.54 and reddening  $E(B - V) = 0.08$  (Keller & Wood, 2006), and  $V$  and  $I$  extinction calculated using the Cardelli et al. (1989) equations. Effective temperatures  $T_{\text{eff}}$  were calculated from a fit to the  $(T_{\text{eff}}, V - I)$  data of Houdashelt et al. (2000), and stellar radii were calculated from luminosity and  $T_{\text{eff}}$  using the Stefan-Boltzmann law. The temperature of the ellipsoidal red giant  $T_{\text{eff}1}$ , an input for both the LC and DC programs of the WD code, was fixed from these calculations. The WD code uses bolometric corrections and bandpass fluxes computed from Kurucz (1993) model atmospheres. After fitting the observed curves, and using the known distance, the code calculates the stellar luminosity. This agreed well with the value computed with the Houdashelt et al. (2000) bolometric corrections, showing consistency of the model atmospheres.

A metallicity of  $[M/H] = -0.3$  was used for these LMC stars. Zero point flux calibrations for the  $I_c$  band (OGLE light curve) and the Johnson  $I$  band (the best match to the wavelengths of the observed spectra from which velocity curves were calculated) were taken from Bessell (1979) and Johnson (1966), respectively. All stars were assumed to have their rotation velocities periastron-synchronised and the rotation parameters  $F_1$  and  $F_2$  were calculated accordingly. The invisible companion star to each ellipsoidal red giant was initially assumed to be a sunlike MS star with  $T_{\text{eff}2} = 6000$  K, and the surface potentials were set so that the companions made no contribution to the modelled light curves. The parameters of the companion were

later adjusted as described below for each case. The potentials of the red giants were set during initial explorations with the LC program so the modelled luminosities and radii matched the independently calculated values.

Solutions for all stars were performed in mode 2, for detached binaries. We used simple reflection treatment with no spots, and no proximity effects. Limb darkening was done via the square root law with coefficients calculated locally from the van Hamme (1993) tables. The stellar atmosphere formulation was used for local flux emission calculations instead of the less accurate blackbody formulation. The gravity darkening exponents were set to 0.3 for each red giant and 1.0 for each MS companion, as appropriate for convective and radiative envelopes, respectively. Bolometric albedos were set to 0.5 for each red giant and 1.0 for each companion, again as expected for convective and radiative envelopes. Symmetric derivatives were used in all solutions to improve convergence.

The inclination was stepped down from  $90^\circ$ , in  $10^\circ$  increments, producing a one-dimensional family of solutions for each system. Stepping of  $i$  stopped when either  $q$  exceeded unity or the solution was deemed too poor. We allowed DC to iterate on  $a$ ,  $e$ ,  $\omega$ , primary star potential  $\Omega_1$ , and  $q$ . The sum of squares of residuals of the light curve was noted for each solution, as a means of quantitatively determining the best solution. In general, solutions converged (so that corrections  $\ll$  errors) in 6 to 8 iterations.

## 5.3.2 Individual star solutions

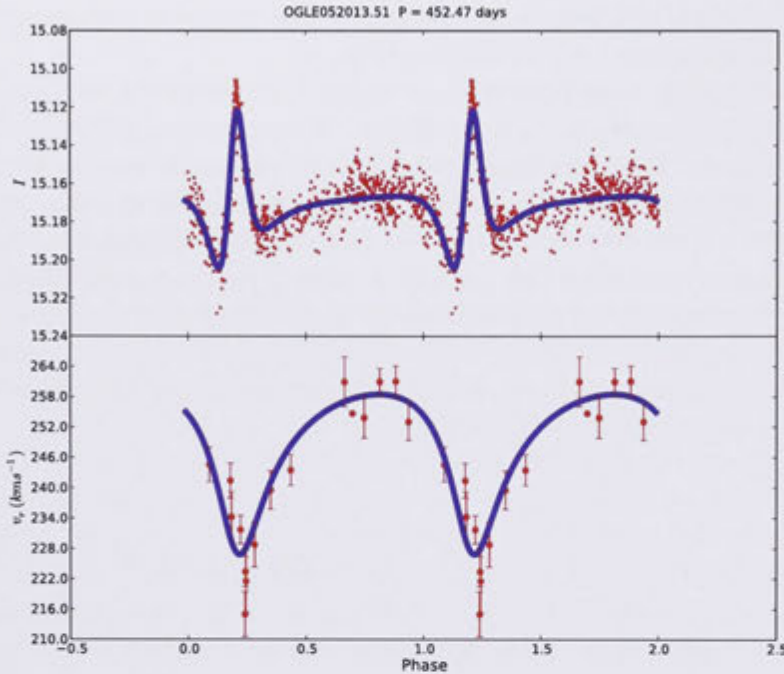
### 5.3.2.1 OGLE052013.51

The observed light and velocity curves are shown in Figure 5.1. The light curve has unequal maxima and minima, with one of the maxima very sharp. At superior conjunction (when the red giant is behind its companion from an observer's point of view), the corresponding minimum of the light curve is deeper, meaning the red giant is dimmer on the end closest its companion. As explained in Nicholls et al. (2010), this is likely due to gravity darkening.

The angle of periastron is  $\sim 160^\circ$ , meaning periastron occurs between superior conjunction and the following maximum, at a phase of  $\sim 0.2$ . This and the high orbital eccentricity ( $\sim 0.4$ ) explains why the brighter maximum is so sharp: in a highly eccentric orbit, a star moves very fast at periastron and so that part of the light curve spans a shorter length of phase. This however cannot explain why the star is brighter there than at its other maximum. An explanation for this brightening is presented in Section 5.4.1.

The results of our modelling for various  $i$  values are shown in Table 5.3, where  $\Sigma r^2(I)$  denotes the sum of squares of residuals of the  $I$ -band light curve from the modelled curve. The errors shown are the standard errors calculated by DC for each adjusted parameter. Semimajor axis,  $e$ ,  $\omega$ ,  $\Omega_1$  and  $q$  all increase significantly with decreasing  $i$ . The mass ratio exceeded unity at  $i = 40^\circ$  so solutions were not made at lower inclinations.

According to the sum of squares of residuals of the light curve, the best solution



**Figure 5.1:** Observed OGLE  $I$  light curve and observed radial velocity curve for OGLE052013.51 (red points) and modelled light and velocity curves (blue lines) at an inclination of  $60^\circ$ .

for a compact secondary is at  $i = 60^\circ$ . This solution was further refined by obtaining more accurate estimates of the MS companion's properties. At  $i = 60^\circ$ , the red giant has a mass of  $1.4 M_\odot$ , and a radius of  $66.3 R_\odot$ . From the colour temperature of  $4220 \text{ K}$ , we calculate the luminosity as  $1252 L_\odot$ . Using the evolutionary track data of Girardi et al. (2000), a red giant of this mass and luminosity and of LMC metallicity should have an age of  $\sim 3 \times 10^9 \text{ yr}$  and be on the RGB. At the same age, the  $1.1 M_\odot$  MS companion should have  $L = 2.4 L_\odot$ ,  $T_{\text{eff}} = 6490 \text{ K}$ , and  $R = 1.2 R_\odot$ . We resolved the system at  $i = 60^\circ$  with  $T_{\text{eff}_2}$  increased to  $6490 \text{ K}$  and the companion's surface potential,  $\Omega_2$ , altered so  $R_2 = 1.2 R_\odot$ . This more accurate solution is shown in the last row of Table 5.3 and in Figure 5.1. Increasing the accuracy of the companion parameters caused no significant changes in the solution.

### 5.3.2.2 OGLE052438.40

From Figure 5.2 it is clear that this variable displays equal maxima and unequal minima. However, the most notable property of this star's light curve is that the deeper minimum occurs at a different place with respect to the velocity curve than expected. Instead of being dimmer towards the companion as gravity darkening dictates, the red giant is dimmer at its other light minimum (inferior conjunction,

**Table 5.3:** Simultaneous light and velocity solutions for OGLE052013.51

| $i$ | $a$ (R $_{\odot}$ ) | $e$               | $\omega$ (radians) | $\Omega_1$        | $q$               | $M_1$ (M $_{\odot}$ ) | $M_2$ (M $_{\odot}$ ) | $R_1$ (R $_{\odot}$ ) | $\Sigma r^2(I)$         |
|-----|---------------------|-------------------|--------------------|-------------------|-------------------|-----------------------|-----------------------|-----------------------|-------------------------|
| 90° | $331.596 \pm 6.065$ | $0.393 \pm 0.005$ | $2.789 \pm 0.007$  | $6.180 \pm 0.165$ | $0.573 \pm 0.045$ | 1.52                  | 0.87                  | 68.61                 | $0.630 \times 10^{-15}$ |
| 80° | $331.749 \pm 5.937$ | $0.396 \pm 0.005$ | $2.791 \pm 0.007$  | $6.243 \pm 0.162$ | $0.594 \pm 0.045$ | 1.50                  | 0.89                  | 68.33                 | $0.616 \times 10^{-15}$ |
| 70° | $331.820 \pm 5.603$ | $0.402 \pm 0.005$ | $2.797 \pm 0.006$  | $6.422 \pm 0.158$ | $0.655 \pm 0.046$ | 1.45                  | 0.95                  | 67.53                 | $0.583 \times 10^{-15}$ |
| 60° | $336.724 \pm 5.194$ | $0.416 \pm 0.005$ | $2.809 \pm 0.006$  | $6.836 \pm 0.155$ | $0.782 \pm 0.047$ | 1.41                  | 1.10                  | 66.32                 | $0.563 \times 10^{-15}$ |
| 50° | $348.620 \pm 5.291$ | $0.442 \pm 0.006$ | $2.830 \pm 0.006$  | $7.478 \pm 0.166$ | $0.949 \pm 0.052$ | 1.43                  | 1.35                  | 65.01                 | $0.663 \times 10^{-15}$ |
| 40° | $372.829 \pm 6.981$ | $0.498 \pm 0.009$ | $2.859 \pm 0.006$  | $8.222 \pm 0.212$ | $1.023 \pm 0.063$ | 1.68                  | 1.72                  | 64.13                 | $0.866 \times 10^{-15}$ |
| 60° | $337.312 \pm 5.130$ | $0.416 \pm 0.005$ | $2.809 \pm 0.006$  | $6.858 \pm 0.154$ | $0.789 \pm 0.046$ | 1.41                  | 1.11                  | 66.29                 | $0.566 \times 10^{-15}$ |



or when the ‘outer end’ of the red giant is towards us). An explanation for this is proposed in Section 5.4.1

The angle of periastron is  $\sim 268^\circ$ , so periastron occurs about the same time as inferior conjunction, or at a phase of  $\sim 0.5$ .

The results of our modelling with different  $i$  values can be found in Table 5.4. For most solutions,  $a$ ,  $e$  and  $\omega$  are not significantly different. However  $\Omega_1$  and  $q$  change significantly with inclination.

According to the sum of squares of residuals of the light curve, the best solution is at  $90^\circ$ . However using the Girardi et al. (2000) evolutionary tracks as above to find the temperature and radius of the MS companion resulted in eclipses in the light curve at both  $90^\circ$  and  $80^\circ$  inclinations. The eclipses disappeared at  $i = 70^\circ$ , where the red giant has a mass of  $5.8 M_\odot$ , and a radius of  $131 R_\odot$ . From the temperature of  $4240 \text{ K}$ , we calculate the luminosity as  $4979 L_\odot$ . A red giant of this mass and luminosity and at LMC metallicity should have an age of  $\sim 7 \times 10^7 \text{ yr}$ , and lie on the RGB. At the same age, the  $5 M_\odot$  MS companion should have  $L = 881 L_\odot$ ,  $T = 16710 \text{ K}$ , and  $R = 3.5 R_\odot$ . We re-solved the system at  $i = 70^\circ$  with  $T_{\text{eff}2}$  increased to  $16710 \text{ K}$  and  $\Omega_2$  altered so  $R_2 = 3.5 R_\odot$ . This solution is shown in the last row of Table 5.4 and in Figure 5.2. The only significant change in parameters for an accurately sized secondary is a slightly higher  $\omega$ . It seems certain that this system has higher mass components than the general LMC intermediate mass population.

### 5.3.2.3 OGLE052812.41

The observed light and velocity curves of this star are depicted in Figure 5.3. Its light curve has unequal maxima and minima, and again the deeper minimum of the light curve occurs at inferior conjunction, instead of at superior conjunction as expected for an ellipsoidal variable.

The angle of periastron of the red giant is  $\sim 215^\circ$ , which means periastron occurs just after the brighter maximum of the light curve, before inferior conjunction, at a phase of  $\sim 0.35$ . Again, proximity of the narrower maximum to periastron is explained by the eccentricity of the orbit.

The solutions for different inclinations are shown in Table 5.5. For most  $i$ ,  $a$  and  $e$  do not differ significantly. Angle of periastron and  $\Omega_1$  vary slightly with  $i$  while  $q$  varies more significantly. Mass ratio exceeded unity at  $i = 50^\circ$ .

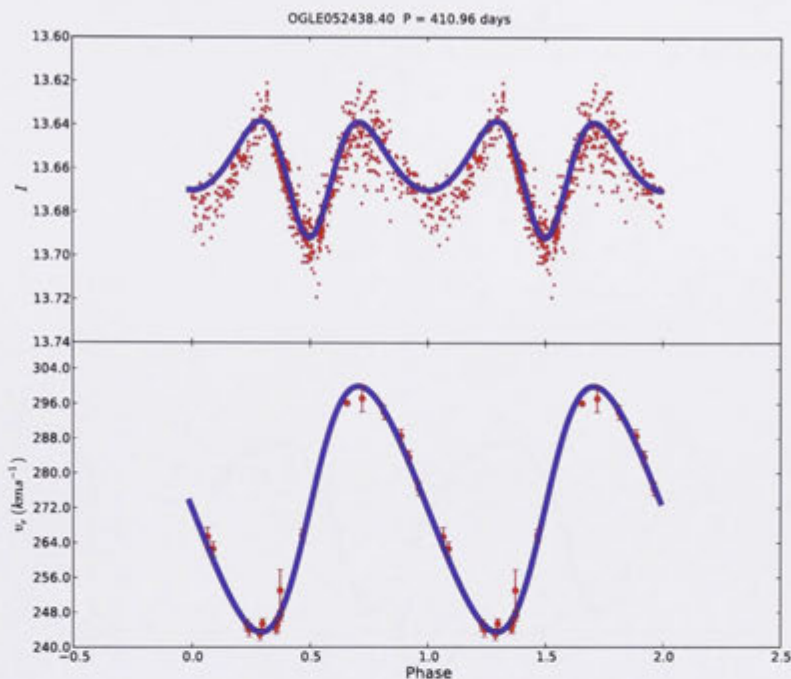
The best solution for a small secondary star is at  $90^\circ$ , according to the sum of squares of residuals of the light curve. This solution was refined further by obtaining more accurate estimates of the MS companion’s properties. At  $i = 90^\circ$ , the red giant has a mass of  $1.4 M_\odot$ , and a radius of  $55.7 R_\odot$ . With a temperature of  $4060 \text{ K}$ , the luminosity is  $756 L_\odot$ . Using the data of Girardi et al. (2000), a red giant of this mass and luminosity at LMC metallicity should have an age of  $\sim 3 \times 10^9 \text{ yr}$ , and lie on the RGB. At the same age, the  $0.9 M_\odot$  MS companion should have  $L = 0.7 L_\odot$ ,  $T = 5790 \text{ K}$ , and  $R = 0.8 R_\odot$ . We further refined our best solution ( $i = 90^\circ$ ) with  $T_{\text{eff}2}$  decreased to  $5790 \text{ K}$  and  $\Omega_2$  altered so  $R_2 = 0.8 R_\odot$ . This solution is shown in the last row of Table 5.5 and in Figure 5.3, and is almost unchanged from the original solution with  $i = 90^\circ$ .

**Table 5.4:** Simultaneous light and velocity solutions for OGLE052438.40

| $i$ | $a$ (R $_{\odot}$ ) | $e$               | $\omega$ (radians) | $\Omega_1$        | $q$               | $M_1$ (M $_{\odot}$ ) | $M_2$ (M $_{\odot}$ ) | $R_1$ (R $_{\odot}$ ) | $\Sigma r^2(I)$         |
|-----|---------------------|-------------------|--------------------|-------------------|-------------------|-----------------------|-----------------------|-----------------------|-------------------------|
| 90° | 515.379 $\pm$ 4.270 | 0.135 $\pm$ 0.006 | 4.640 $\pm$ 0.033  | 4.880 $\pm$ 0.050 | 0.770 $\pm$ 0.019 | 6.15                  | 4.74                  | 131.41                | 0.699 $\times 10^{-14}$ |
| 80° | 514.782 $\pm$ 4.269 | 0.135 $\pm$ 0.006 | 4.633 $\pm$ 0.033  | 4.904 $\pm$ 0.050 | 0.791 $\pm$ 0.019 | 6.06                  | 4.79                  | 131.30                | 0.700 $\times 10^{-14}$ |
| 70° | 513.360 $\pm$ 4.189 | 0.134 $\pm$ 0.006 | 4.635 $\pm$ 0.033  | 4.997 $\pm$ 0.052 | 0.869 $\pm$ 0.021 | 5.76                  | 5.00                  | 130.96                | 0.700 $\times 10^{-14}$ |
| 60° | 511.935 $\pm$ 4.319 | 0.130 $\pm$ 0.006 | 4.631 $\pm$ 0.035  | 5.186 $\pm$ 0.058 | 1.025 $\pm$ 0.026 | 5.27                  | 5.40                  | 130.35                | 0.703 $\times 10^{-14}$ |
| 50° | 511.608 $\pm$ 4.446 | 0.122 $\pm$ 0.005 | 4.624 $\pm$ 0.039  | 5.576 $\pm$ 0.070 | 1.342 $\pm$ 0.036 | 4.55                  | 6.10                  | 129.36                | 0.715 $\times 10^{-14}$ |
| 70° | 511.549 $\pm$ 4.994 | 0.138 $\pm$ 0.006 | 4.676 $\pm$ 0.034  | 5.064 $\pm$ 0.074 | 0.899 $\pm$ 0.031 | 5.61                  | 5.04                  | 129.55                | 0.543 $\times 10^{-14}$ |

**Table 5.5:** Simultaneous light and velocity solutions for OGLE052812.41

| $i$ | $a \text{ (R}_\odot\text{)}$ | $e$               | $\omega \text{ (radians)}$ | $\Omega_1$        | $q$               | $M_1 \text{ (M}_\odot\text{)}$ | $M_2 \text{ (M}_\odot\text{)}$ | $R_1 \text{ (R}_\odot\text{)}$ | $\Sigma r^2(I)$         |
|-----|------------------------------|-------------------|----------------------------|-------------------|-------------------|--------------------------------|--------------------------------|--------------------------------|-------------------------|
| 90° | $225.412 \pm 4.920$          | $0.237 \pm 0.007$ | $3.758 \pm 0.022$          | $4.985 \pm 0.145$ | $0.652 \pm 0.045$ | 1.39                           | 0.91                           | 55.65                          | $0.182 \times 10^{-15}$ |
| 80° | $225.634 \pm 4.906$          | $0.236 \pm 0.007$ | $3.752 \pm 0.022$          | $5.025 \pm 0.147$ | $0.675 \pm 0.047$ | 1.38                           | 0.93                           | 55.60                          | $0.183 \times 10^{-15}$ |
| 70° | $226.185 \pm 4.633$          | $0.236 \pm 0.007$ | $3.741 \pm 0.022$          | $5.148 \pm 0.145$ | $0.750 \pm 0.049$ | 1.33                           | 1.00                           | 55.44                          | $0.184 \times 10^{-15}$ |
| 60° | $223.762 \pm 4.280$          | $0.234 \pm 0.007$ | $3.712 \pm 0.023$          | $5.257 \pm 0.141$ | $0.849 \pm 0.052$ | 1.22                           | 1.03                           | 55.17                          | $0.191 \times 10^{-15}$ |
| 50° | $221.307 \pm 4.066$          | $0.225 \pm 0.008$ | $3.663 \pm 0.025$          | $5.466 \pm 0.145$ | $1.023 \pm 0.059$ | 1.08                           | 1.10                           | 54.76                          | $0.215 \times 10^{-15}$ |
| 90° | $224.800 \pm 4.926$          | $0.236 \pm 0.007$ | $3.755 \pm 0.022$          | $4.965 \pm 0.144$ | $0.644 \pm 0.045$ | 1.39                           | 0.89                           | 55.64                          | $0.183 \times 10^{-15}$ |



**Figure 5.2:** Observed OGLE  $I$  light curve and observed radial velocity curve for OGLE052438.40 (red points) and modelled light and velocity curves (blue lines) at an inclination of  $70^\circ$ .

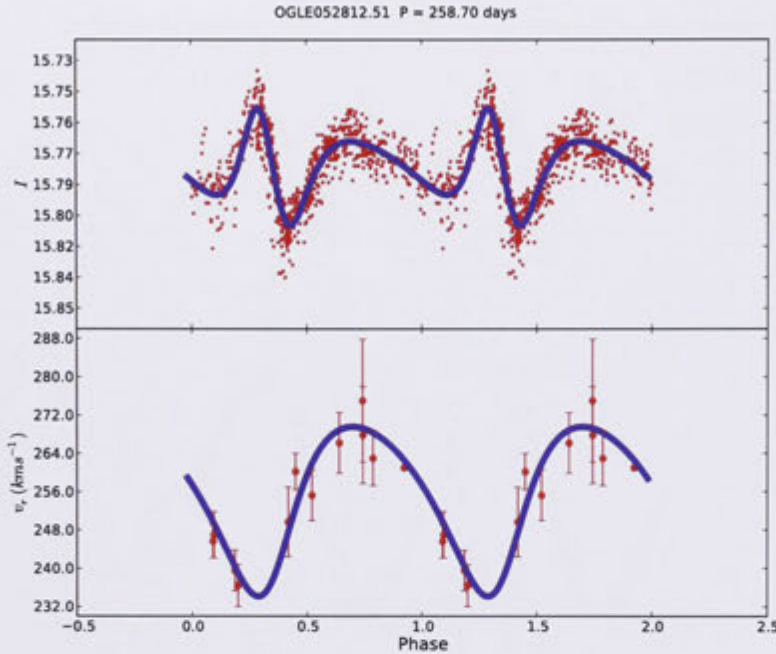
#### 5.3.2.4 OGLE052850.12

The observed light and radial velocity curves are shown in Figure 5.4. The light curve shows unequal maxima and minima of almost equal depths.

The angle of periastron is  $\sim 188^\circ$ , so periastron occurs almost concurrently with the brighter light maximum, at a phase of  $\sim 0.27$ . The narrower maximum is again due to the star moving quickly at periastron during this part of its orbit. The slight asymmetry of the dimmer maximum, and the fact that the fit was unable to reproduce this, is likely due to a non-standard temperature distribution across the ellipsoidal red giant's surface.

The results are shown in Table 5.6. Semimajor axis,  $e$ ,  $\omega$ , and  $\Omega_1$  vary slowly with  $i$ , while  $q$  changes rapidly with  $i$ , particularly at low inclinations, and exceeds unity at  $i = 40^\circ$ .

According to the sum of the squares of residuals of the light curve, the best solution is at  $i = 50^\circ$ . This solution was further refined by obtaining more accurate estimates of the MS companion's properties. At  $i = 50^\circ$ , the red giant has a mass of  $4.3 M_\odot$ , and a radius of  $176 R_\odot$ . From the colour temperature of  $3720 \text{ K}$ , we calculate the luminosity as  $5325 L_\odot$ . A red giant of this mass and luminosity and at LMC metallicity should have an age of  $\sim 1.5 \times 10^8 \text{ yr}$  and be on the AGB. At



**Figure 5.3:** Observed OGLE  $I$  light curve and observed radial velocity curve for OGLE052812.41 (red points) and modelled light and velocity curves (blue lines) at an inclination of  $90^\circ$ .

the same age, the  $3.4 M_\odot$  MS companion should have  $L = 242 L_\odot$ ,  $T = 13430$  K, and  $R = 2.88 R_\odot$ . We re-solved this solution with  $T_{\text{eff}2}$  increased to  $13430$  K and  $\Omega_2$  altered so  $R_2 = 2.88 R_\odot$ . This solution is shown in the last row of Table 5.6 and in Figure 5.4.

### 5.3.2.5 OGLE053033.55

The observed light and velocity curves are depicted in Figure 5.5. This star also shows unequal maxima and minima, with the deeper minimum of the light curve at inferior conjunction.

The angle of periastron is  $\sim 290^\circ$ , with periastron occurring between inferior conjunction and the following light maximum, at a phase of  $\sim 0.55$ .

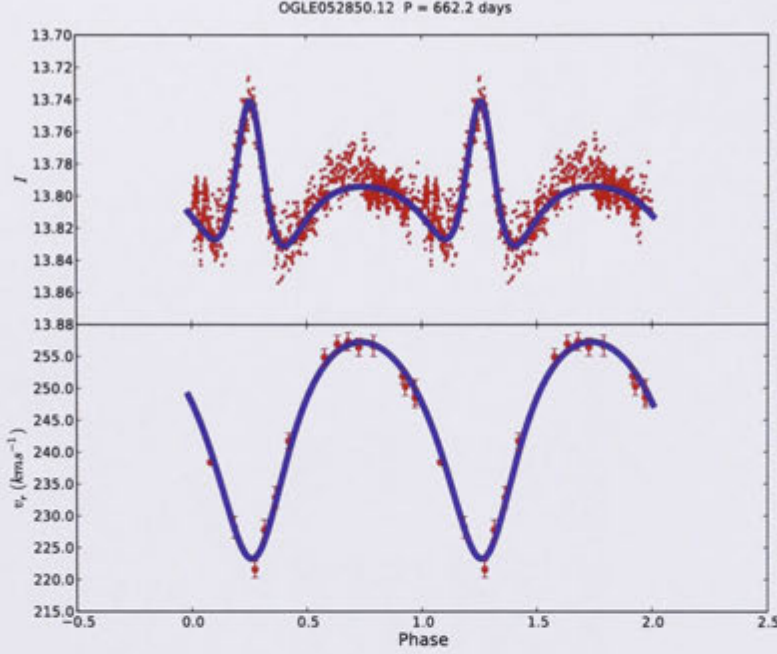
The solutions for all modelled inclinations and a compact secondary are shown in Table 5.7. Semimajor axis,  $e$ ,  $\omega$ ,  $\Omega_1$  and  $q$  all vary significantly with  $i$ . The mass ratio exceeded unity at  $i = 30^\circ$ , and we did not make solutions at lower inclinations.

According to the sum of squares of residuals of the light curve, the best solution is at  $60^\circ$ . We further refined this solution by obtaining more accurate estimates of the MS companion's properties. At  $i = 60^\circ$ , the red giant has a mass of  $5.8 M_\odot$ , and a radius of  $123 R_\odot$ . The colour temperature of  $4180$  K gives a luminosity of  $4147 L_\odot$ . Using the data of Girardi et al. (2000), a red giant of this mass and luminosity and

**Table 5.6:** Simultaneous light and velocity solutions for OGLE052850.12

| $i$ | $a$ (R $_{\odot}$ ) | $e$               | $\omega$ (radians) | $\Omega_1$        | $q$               | $M_1$ (M $_{\odot}$ ) | $M_2$ (M $_{\odot}$ ) | $R_1$ (R $_{\odot}$ ) | $\Sigma r^2(I)$         |
|-----|---------------------|-------------------|--------------------|-------------------|-------------------|-----------------------|-----------------------|-----------------------|-------------------------|
| 90° | 648.261 $\pm$ 6.646 | 0.241 $\pm$ 0.005 | 3.368 $\pm$ 0.021  | 4.302 $\pm$ 0.056 | 0.466 $\pm$ 0.016 | 5.69                  | 2.65                  | 182.79                | 0.201 $\times 10^{-13}$ |
| 80° | 649.654 $\pm$ 5.285 | 0.244 $\pm$ 0.005 | 3.359 $\pm$ 0.020  | 4.352 $\pm$ 0.044 | 0.489 $\pm$ 0.013 | 5.64                  | 2.76                  | 182.38                | 0.198 $\times 10^{-13}$ |
| 70° | 642.750 $\pm$ 4.315 | 0.249 $\pm$ 0.005 | 3.355 $\pm$ 0.018  | 4.416 $\pm$ 0.036 | 0.540 $\pm$ 0.011 | 5.28                  | 2.85                  | 181.26                | 0.185 $\times 10^{-13}$ |
| 60° | 632.234 $\pm$ 6.562 | 0.255 $\pm$ 0.005 | 3.326 $\pm$ 0.016  | 4.526 $\pm$ 0.065 | 0.623 $\pm$ 0.022 | 4.77                  | 2.97                  | 179.32                | 0.167 $\times 10^{-13}$ |
| 50° | 630.260 $\pm$ 4.228 | 0.254 $\pm$ 0.005 | 3.286 $\pm$ 0.015  | 4.821 $\pm$ 0.045 | 0.796 $\pm$ 0.018 | 4.27                  | 3.40                  | 176.43                | 0.155 $\times 10^{-13}$ |
| 40° | 639.198 $\pm$ 5.137 | 0.228 $\pm$ 0.006 | 3.256 $\pm$ 0.019  | 5.350 $\pm$ 0.063 | 1.114 $\pm$ 0.030 | 3.79                  | 4.22                  | 172.54                | 0.196 $\times 10^{-13}$ |
| 50° | 628.582 $\pm$ 5.807 | 0.252 $\pm$ 0.005 | 3.287 $\pm$ 0.015  | 4.835 $\pm$ 0.068 | 0.807 $\pm$ 0.027 | 4.21                  | 3.40                  | 175.93                | 0.155 $\times 10^{-13}$ |





**Figure 5.4:** Observed OGLE  $I$  light curve and observed radial velocity curve for OGLE052850.12 (red points) and modelled light and velocity curves (blue lines) at an inclination of  $60^\circ$ .

at LMC metallicity should have an age of  $\sim 7 \times 10^7$  yr, and lie on the RGB. At the same age, the  $3.2 M_\odot$  MS companion should have  $L = 99 L_\odot$ ,  $T = 13310$  K, and  $R = 1.9 R_\odot$ . We re-solved at  $i = 60^\circ$  with  $T_{\text{eff}2}$  increased to 13310 K and  $\Omega_2$  altered so  $R_2 = 1.9 R_\odot$ . This solution is shown in the last row of Table 5.7 and in Figure 5.5. The masses in this system are again higher than the typical LMC field population.

### 5.3.2.6 OGLE053124.49

The observed light and velocity curves are shown in Figure 5.6, from which it is clear that this star also shows unequal maxima and minima in its light curve. At superior conjunction, the relevant minimum of the light curve is deeper, i.e. the star is dimmer on the end nearest the companion, as expected due to gravity darkening.

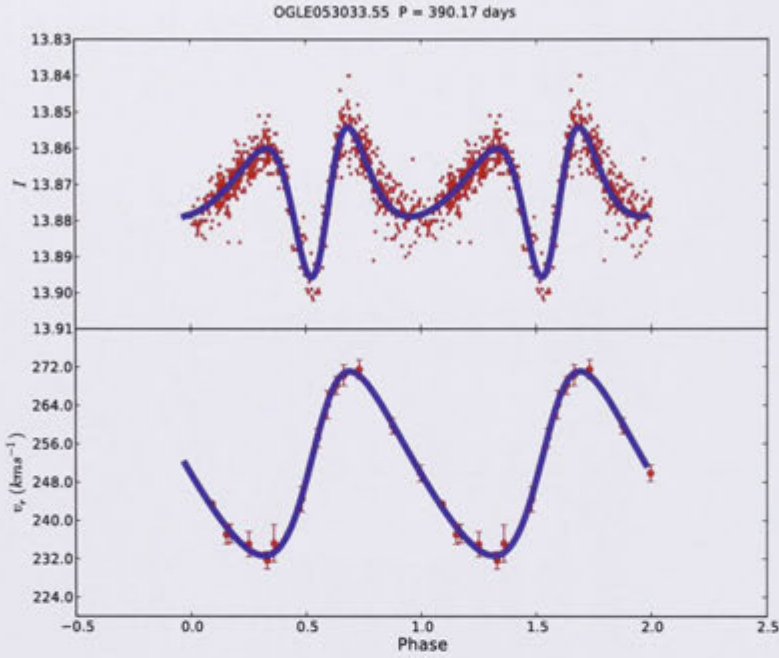
The angle of periastron is  $\sim 176^\circ$ , so periastron occurs around the same time as the brighter maximum, at a phase of  $\sim 0.24$ . Again the narrow maximum can be attributed to the star moving fast at periastron in a highly eccentric orbit, but this does not explain why this maximum is brighter than the other.

The results of the WD modelling are shown in Table 5.8. Semimajor axis,  $e$ , and  $\omega$  all vary slightly with decreasing  $i$ , while  $\Omega_1$  and  $q$  vary more significantly with  $i$ .

The best solution with a compact secondary is at  $90^\circ$ , according to the sum of squares of residuals of the light curve. However using the Girardi et al. (2000)

**Table 5.7:** Simultaneous light and velocity solutions for OGLE053033.55

| $i$ | $a$ (R $_{\odot}$ ) | $e$               | $\omega$ (radians) | $\Omega_1$        | $q$               | $M_1$ (M $_{\odot}$ ) | $M_2$ (M $_{\odot}$ ) | $R_1$ (R $_{\odot}$ ) | $\Sigma r^2(I)$         |
|-----|---------------------|-------------------|--------------------|-------------------|-------------------|-----------------------|-----------------------|-----------------------|-------------------------|
| 90° | 475.000 $\pm$ 3.171 | 0.215 $\pm$ 0.005 | 5.005 $\pm$ 0.022  | 4.462 $\pm$ 0.033 | 0.437 $\pm$ 0.008 | 6.58                  | 2.87                  | 124.18                | 0.147 $\times 10^{-14}$ |
| 80° | 474.346 $\pm$ 3.290 | 0.215 $\pm$ 0.005 | 5.009 $\pm$ 0.022  | 4.476 $\pm$ 0.035 | 0.448 $\pm$ 0.009 | 6.50                  | 2.92                  | 124.06                | 0.146 $\times 10^{-14}$ |
| 70° | 471.506 $\pm$ 2.823 | 0.214 $\pm$ 0.005 | 5.026 $\pm$ 0.022  | 4.512 $\pm$ 0.029 | 0.485 $\pm$ 0.008 | 6.23                  | 3.02                  | 123.72                | 0.144 $\times 10^{-14}$ |
| 60° | 467.796 $\pm$ 2.655 | 0.210 $\pm$ 0.005 | 5.052 $\pm$ 0.022  | 4.594 $\pm$ 0.027 | 0.556 $\pm$ 0.009 | 5.80                  | 3.23                  | 123.14                | 0.142 $\times 10^{-14}$ |
| 50° | 464.284 $\pm$ 2.719 | 0.201 $\pm$ 0.005 | 5.077 $\pm$ 0.023  | 4.758 $\pm$ 0.030 | 0.689 $\pm$ 0.011 | 5.23                  | 3.60                  | 122.29                | 0.145 $\times 10^{-14}$ |
| 40° | 463.957 $\pm$ 3.208 | 0.170 $\pm$ 0.005 | 5.070 $\pm$ 0.028  | 5.087 $\pm$ 0.041 | 0.949 $\pm$ 0.019 | 4.52                  | 4.29                  | 121.09                | 0.169 $\times 10^{-14}$ |
| 30° | 472.820 $\pm$ 3.927 | 0.108 $\pm$ 0.004 | 4.982 $\pm$ 0.037  | 5.878 $\pm$ 0.058 | 1.579 $\pm$ 0.036 | 3.62                  | 5.71                  | 119.24                | 0.276 $\times 10^{-14}$ |
| 60° | 465.730 $\pm$ 2.482 | 0.212 $\pm$ 0.005 | 5.053 $\pm$ 0.021  | 4.594 $\pm$ 0.025 | 0.560 $\pm$ 0.008 | 5.72                  | 3.20                  | 122.76                | 0.141 $\times 10^{-14}$ |



**Figure 5.5:** Observed OGLE  $I$  light curve and observed radial velocity curve for OGLE053033.55 (red points) and modelled light and velocity curves (blue lines) at an inclination of  $60^\circ$ .

evolutionary tracks as above to find the temperature and radius of the MS companion resulted in eclipses of the light curve at  $90^\circ$  and  $80^\circ$ . The eclipses disappeared at  $i = 70^\circ$ , where the red giant has a mass of  $2.0 M_\odot$ , and a radius of  $92 R_\odot$ . From the colour temperature of 3880 K, the luminosity is  $1722 L_\odot$ . From Girardi et al. (2000), a red giant of this mass and luminosity and at LMC metallicity has an age of  $\sim 1.3 \times 10^9$  yr, and is an AGB star around the time of its first thermal pulse. At the same age, the  $1 M_\odot$  MS companion should have  $L = 1.19 L_\odot$ ,  $T = 6120$  K, and  $R = 0.97 R_\odot$ . We re-ran the code at  $i = 70^\circ$  with  $T_{\text{eff}2}$  increased to 6120 K and  $\Omega_2$  altered so  $R_2 = 0.97 R_\odot$ . This solution is shown in the last row of Table 5.8 and in Figure 5.6.

### 5.3.2.7 OGLE053159.96

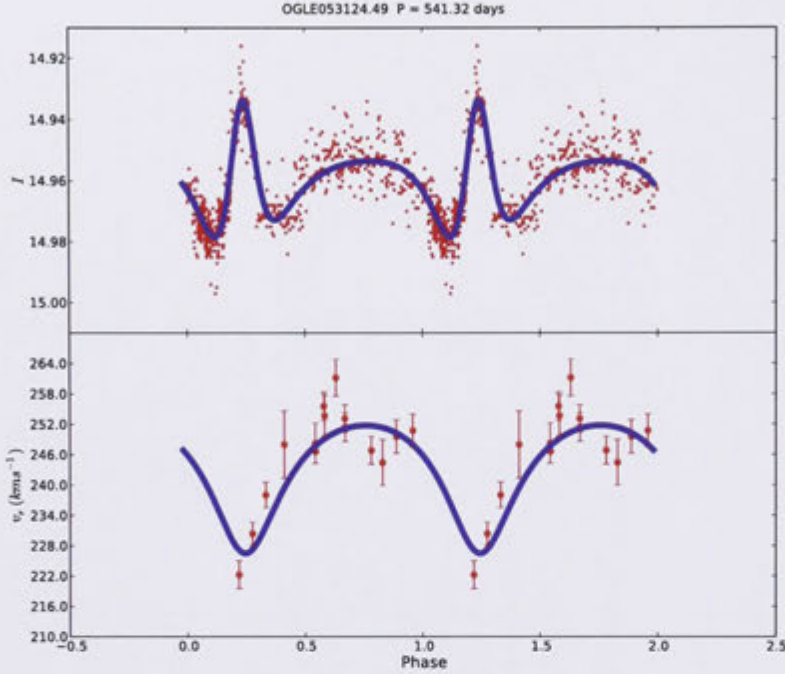
The observed light and velocity curves are shown in Figure 5.7. This star has a light curve with unequal maxima and minima, and again its deeper light minimum occurs at inferior conjunction.

The angle of periastron is  $\sim 280^\circ$ , so periastron occurs between inferior conjunction and the subsequent light maximum, at a phase of  $\sim 0.53$ . In this case, periastron has squeezed the deeper minimum in phase, rather than one of the maxima.

The solutions are shown in Table 5.9. Semimajor axis,  $e$ , and  $\omega$  all vary slowly

**Table 5.8:** Simultaneous light and velocity solutions for OGLE053124.49

| $i$ | $a$ (R $_{\odot}$ ) | $e$               | $\omega$ (radians) | $\Omega_1$        | $q$               | $M_1$ (M $_{\odot}$ ) | $M_2$ (M $_{\odot}$ ) | $R_1$ (R $_{\odot}$ ) | $\Sigma r^2(I)$         |
|-----|---------------------|-------------------|--------------------|-------------------|-------------------|-----------------------|-----------------------|-----------------------|-------------------------|
| 90° | 407.136 $\pm$ 6.991 | 0.286 $\pm$ 0.006 | 3.071 $\pm$ 0.019  | 5.188 $\pm$ 0.113 | 0.467 $\pm$ 0.029 | 2.11                  | 0.99                  | 93.00                 | 0.352 $\times 10^{-15}$ |
| 80° | 405.453 $\pm$ 5.977 | 0.288 $\pm$ 0.006 | 3.071 $\pm$ 0.019  | 5.193 $\pm$ 0.097 | 0.476 $\pm$ 0.025 | 2.07                  | 0.99                  | 92.86                 | 0.353 $\times 10^{-15}$ |
| 70° | 403.084 $\pm$ 5.348 | 0.294 $\pm$ 0.006 | 3.072 $\pm$ 0.019  | 5.258 $\pm$ 0.087 | 0.518 $\pm$ 0.023 | 1.98                  | 1.02                  | 92.40                 | 0.356 $\times 10^{-15}$ |
| 60° | 399.950 $\pm$ 5.083 | 0.302 $\pm$ 0.007 | 3.079 $\pm$ 0.019  | 5.389 $\pm$ 0.085 | 0.595 $\pm$ 0.025 | 1.84                  | 1.09                  | 91.64                 | 0.379 $\times 10^{-15}$ |
| 50° | 399.535 $\pm$ 5.523 | 0.306 $\pm$ 0.008 | 3.107 $\pm$ 0.020  | 5.653 $\pm$ 0.098 | 0.733 $\pm$ 0.032 | 1.69                  | 1.24                  | 90.59                 | 0.465 $\times 10^{-15}$ |
| 40° | 408.102 $\pm$ 7.726 | 0.295 $\pm$ 0.012 | 3.194 $\pm$ 0.027  | 6.144 $\pm$ 0.153 | 0.972 $\pm$ 0.059 | 1.58                  | 1.54                  | 89.37                 | 0.699 $\times 10^{-15}$ |
| 30° | 377.018 $\pm$ 8.088 | 0.083 $\pm$ 0.014 | 4.184 $\pm$ 0.087  | 6.516 $\pm$ 0.161 | 1.700 $\pm$ 0.086 | 0.91                  | 1.55                  | 86.47                 | 1.150 $\times 10^{-15}$ |
| 70° | 402.608 $\pm$ 6.848 | 0.292 $\pm$ 0.006 | 3.076 $\pm$ 0.018  | 5.254 $\pm$ 0.116 | 0.519 $\pm$ 0.032 | 1.97                  | 1.02                  | 92.40                 | 0.356 $\times 10^{-15}$ |



**Figure 5.6:** Observed OGLE  $I$  light curve and observed radial velocity curve for OGLE053124.49 (red points) and modelled light and velocity curves (blue lines) at an inclination of  $70^\circ$ .

with  $i$ . Primary potential and  $q$  vary significantly with  $i$ . The stepping down of  $i$  for successive solutions was halted before  $q$  exceeded unity, as at  $i = 40^\circ$  DC was unable to fit the full amplitude of the light curve.

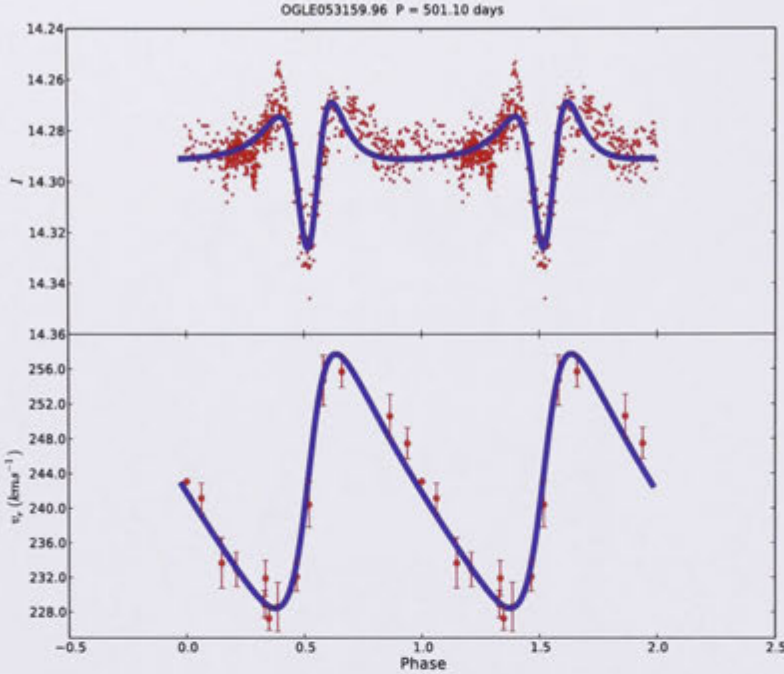
According to the sum of squares of residuals of the light curve, the best solution is at  $i = 80^\circ$ . However using a more accurate temperature and radius for the MS companion results in eclipses at  $80^\circ$  and  $70^\circ$ , due to the increased radius of the MS star. The eclipses disappeared at  $i = 60^\circ$ , where the red giant has a mass of  $4.8 M_\odot$ , and a radius of  $125 R_\odot$ . With a colour temperature of  $3880 \text{ K}$ , the red giant's luminosity is  $3179 L_\odot$ . Using the data of Girardi et al. (2000), a red giant of this mass and luminosity and LMC metallicity should have an age of  $\sim 1.05 \times 10^8 \text{ yr}$ , and be at or near the RGB tip. At the same age, the  $2.1 M_\odot$  MS companion should have  $L = 35 L_\odot$ ,  $T = 10590 \text{ K}$ , and  $R = 1.76 R_\odot$ . We further refined our best solution ( $i = 60^\circ$ ) with  $T_{\text{eff}2}$  increased to  $10590 \text{ K}$  and  $\Omega_2$  altered so  $R_2 = 1.76 R_\odot$ . This solution is shown in the last row of Table 5.9 and in Figure 5.7. This star also has higher mass than expected for the general LMC field population.



**Table 5.9:** Simultaneous light and velocity solutions for OGLE053159.96

| $i$ | $a$ (R $_{\odot}$ ) | $e$               | $\omega$ (radians) | $\Omega_1$        | $q$               | $M_1$ (M $_{\odot}$ ) | $M_2$ (M $_{\odot}$ ) | $R_1$ (R $_{\odot}$ ) | $\Sigma r^2(I)$                 |
|-----|---------------------|-------------------|--------------------|-------------------|-------------------|-----------------------|-----------------------|-----------------------|---------------------------------|
| 90° | 525.077 $\pm$ 4.739 | 0.405 $\pm$ 0.008 | 4.874 $\pm$ 0.012  | 4.859 $\pm$ 0.044 | 0.336 $\pm$ 0.088 | 5.80                  | 1.95                  | 126.84                | 0.19 $\times$ 10 <sup>-14</sup> |
| 80° | 522.302 $\pm$ 7.409 | 0.405 $\pm$ 0.008 | 4.866 $\pm$ 0.012  | 4.856 $\pm$ 0.081 | 0.342 $\pm$ 0.016 | 5.68                  | 1.94                  | 126.65                | 0.19 $\times$ 10 <sup>-14</sup> |
| 70° | 516.514 $\pm$ 5.895 | 0.400 $\pm$ 0.007 | 4.872 $\pm$ 0.012  | 4.886 $\pm$ 0.062 | 0.375 $\pm$ 0.013 | 5.36                  | 2.01                  | 126.05                | 0.19 $\times$ 10 <sup>-14</sup> |
| 60° | 505.586 $\pm$ 5.025 | 0.390 $\pm$ 0.007 | 4.881 $\pm$ 0.013  | 4.937 $\pm$ 0.052 | 0.436 $\pm$ 0.013 | 4.81                  | 2.10                  | 125.03                | 0.19 $\times$ 10 <sup>-14</sup> |
| 50° | 492.890 $\pm$ 4.874 | 0.367 $\pm$ 0.007 | 4.898 $\pm$ 0.016  | 5.062 $\pm$ 0.050 | 0.550 $\pm$ 0.015 | 4.13                  | 2.27                  | 123.48                | 0.21 $\times$ 10 <sup>-14</sup> |
| 40° | 489.737 $\pm$ 7.847 | 0.305 $\pm$ 0.009 | 4.946 $\pm$ 0.028  | 5.380 $\pm$ 0.103 | 0.778 $\pm$ 0.038 | 3.53                  | 2.75                  | 121.42                | 0.27 $\times$ 10 <sup>-14</sup> |
| 60° | 505.150 $\pm$ 6.698 | 0.391 $\pm$ 0.007 | 4.877 $\pm$ 0.013  | 4.948 $\pm$ 0.079 | 0.439 $\pm$ 0.020 | 4.79                  | 2.10                  | 124.72                | 0.19 $\times$ 10 <sup>-14</sup> |





**Figure 5.7:** Observed OGLE  $I$  light curve and observed radial velocity curve for OGLE053159.96 (red points) and modelled light and velocity curves (blue lines) at an inclination of  $60^\circ$ .

## 5.4 Discussion

All the stars in our sample clearly show the doubling of the light curve with respect to the velocity curve that is the hallmark of ellipsoidal variation. All the light curves display minima of unequal depths, another common property of ellipsoidal variables. In variables with circular orbits, the deeper minimum is caused by gravity darkening on the inner end of the ellipsoidal red giant. In that case the deeper minimum should be found at superior conjunction, however for most of our eccentric sample the opposite is true.

The majority of stars in our sample also show maxima of unequal heights in their light curves, a phenomenon that was not seen in ellipsoidal variables with small or zero eccentricity (Nicholls et al., 2010). A possible explanation for the unequal maxima and the unexpected placement of the deeper minimum in eccentric ellipsoidal variables is presented in Section 5.4.1.

Many stars in our sample are more massive and more luminous than the average LMC red giant. According to the evolutionary tracks of Girardi et al. (2000), two are AGB stars. This is likely to be mostly due to a luminosity selection effect, as we selected the brightest eccentric candidates from the OGLE database to obtain targets suitable for our observing facilities. Selecting variables with high eccentricity

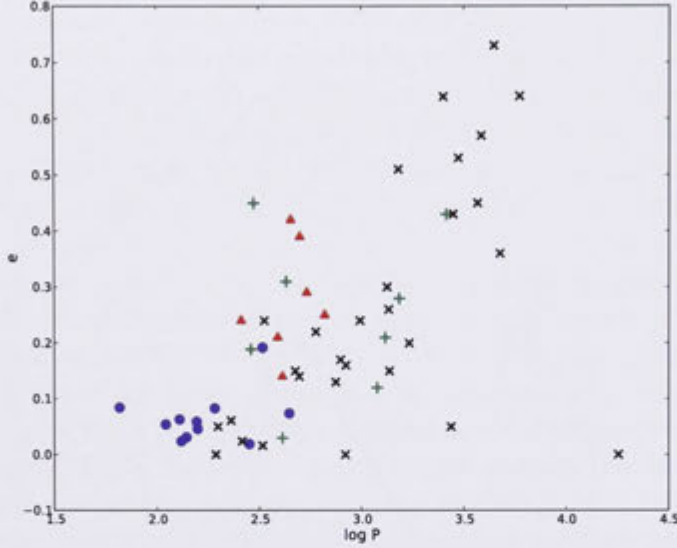
is also likely to mean longer average orbital periods and hence higher luminosities, since Soszyński et al. (2004b) noted that the eccentric ellipsoidal variables in their sample generally had longer periods than the low-eccentricity variables. We note that it is unclear why higher eccentricity and longer periods should be linked in the case of ellipsoidal variables, since tidal circularisation time depends not on orbital separation (i.e. period) but very sensitively on fractional lobe filling ( $a/R$ ).

The inclinations of our sample are between  $50^\circ$  and  $90^\circ$ , with a mean inclination of  $66^\circ$ . A bias towards high inclinations is expected for ellipsoidal variation, which should not be detectable at very low inclinations, although ellipsoids with a large fractional lobe filling may be visible as low-amplitude variables at inclinations as low as  $30^\circ$ . It is interesting to note that although ellipsoidal variation would certainly be visible in edge-on orbits, in our sample of variables without eclipses, inclinations this high are unlikely unless the companion is particularly small. However in many of our systems, both components are intermediate mass stars ( $M \gtrsim 1.85 M_\odot$ ), meaning that the radius ratio of red giant to main sequence star is not very large (as it is for low mass stars,  $M \lesssim 1.85 M_\odot$ ). In this situation, the companions will cause easily detected eclipses, so by selecting non-eclipsing variables we have unwittingly selected fewer edge-on orbits. In a more representative sample of non-eclipsing ellipsoidal variables with lower average mass (closer to the LMC average), and with relatively smaller companion radii that do not cause observable eclipses even in edge-on orbits, we suspect the mean orbital inclination would be higher.

We have confirmed the hypothesis of Soszyński et al. (2004b), that ellipsoidal light curves with strange shapes represent eccentric orbits. The eccentricities of all stars in our sample are significantly nonzero and generally high, ranging from 0.14 to 0.42. The mean eccentricity of the sample is 0.28. Figure 5.8 shows the location of these eccentric ellipsoidal variables in the  $(e, \log P)$  plane compared to other evolved binaries. At short periods, eccentricities are lower as expected from tidal theory. This graph is a vivid demonstration of the surprisingly high eccentricities found amongst many evolved binaries. According to Izzard et al. (2010), population synthesis studies of Ba stars predict all orbits  $< 4000$  days should be circular, a result that is at complete odds with observations. The diverse range of periods, masses and evolutionary states of binaries that seem to have somehow escaped the circularising effect of tidal forces serves to reinforce the need for an understanding of the mechanism that maintains or increases eccentricity.

The full velocity amplitudes of our sample lie between 25 and  $56 \text{ km s}^{-1}$ , with a mean of  $35.8 \text{ km s}^{-1}$ . Figure 5.9 shows that the current sample of ellipsoidal variables with high eccentricities falls within the velocity amplitude distribution of the ellipsoidal variables with mostly circular orbits presented in Nicholls et al. (2010). However the eccentric variables generally lie at longer periods. Also shown in Figure 5.9 are a sample of LSPVs from Nicholls et al. (2009), once again demonstrating the marked difference between stars with Long Secondary Periods and ellipsoidal variables.

Two individual stars are worthy of comment. OGLE052850.12 is the brightest and coolest star in our sample, with the largest light amplitude, meaning it is nearly filling its Roche Lobe. It is of relatively high mass ( $\sim 4.2 M_\odot$ ) but not the highest



**Figure 5.8:** Eccentricity vs. period for the current sample of eccentric ellipsoidal variables (red triangles); the low- $e$  ellipsoidal sample of Nicholls et al. (2010) (blue circles); post-AGB stars from Waters et al. (1993); Van Winckel et al. (1995, 1998, 1999); Pollard & Cottrell (1995); and Gonzalez & Wallerstein (1996) (green pluses); and M giant binaries from Famaey et al. (2009) (black crosses).

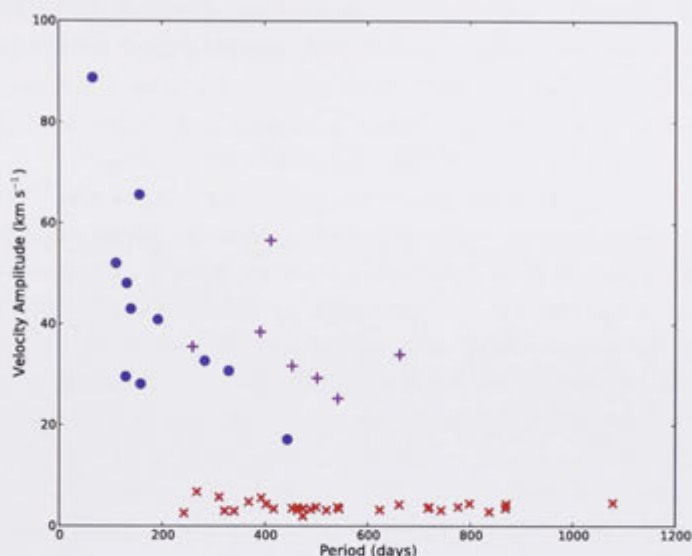
in our sample. According to the evolutionary tracks of Girardi et al. (2000) it is an AGB star, which explains the obvious pulsations in its light curve. There is a very real possibility that this object will fill its Roche Lobe before it reaches the AGB tip and become a PN, possibly of asymmetric shape, with a close binary central star.

OGLE053124.49 is the most evolved star in our sample, and according to the evolutionary tracks is an AGB star near the time of its first thermal pulse. It has one of the smallest light amplitudes in our sample, suggesting a low fractional lobe filling (as its inclination is similar to that of OGLE052850.12). Given its advanced evolutionary state and low fractional lobe filling, it is possible that this star may not fill its Roche Lobe before it reaches the AGB tip and may lose its envelope via the superwind as single AGB stars do, leaving a remnant PN with a wide binary companion.

#### 5.4.1 Increased Distortion in High Eccentricity Orbits

It has been noted above that many of the eccentric ellipsoidal variables in our sample show unequal maxima as well as unequal minima in their light curves. As Nicholls et al. (2010) showed, in normal circumstances the deeper minimum is caused by gravity darkening of the red giant on the side nearest its companion and should therefore occur at superior conjunction. In this regime there is also no reason why





**Figure 5.9:** Full velocity amplitude vs. period for the current sample of eccentric ellipsoidal variables (magenta pluses), the mostly circular ellipsoidal sample of Nicholls et al. (2010) (blue circles), and the LSPV sample of Nicholls et al. (2009) (red crosses).

the light maxima should be unequal.

From a glance at the phased light and velocity curves of the current sample, it is clear that for many stars, the deeper light minimum occurs at inferior, not superior, conjunction. This suggests that when the ‘outer end’ of the ellipsoidal red giant is facing us, the star appears dimmer due to some effect outweighing the gravity darkening of the ‘inner end’.

A related phenomenon occurs with maxima. For 6 of the 7 stars, one of the light maxima is narrower and brighter than the other. The narrowness of this maximum – its shorter span in phase – can be explained by its proximity to periastron and the eccentricity of the orbit. At periastron in a highly eccentric orbit, the star moves significantly faster than at apastron, so that part of the light curve appears ‘squashed’ in phase. But what causes a maximum to be brighter as well as narrower when it lies close to periastron?

The results of our modelling show that the deeper light minimum and the brighter maximum are always close to periastron. Given the high eccentricity of these orbits, here we suggest that the cause of these unequal maxima and minima, and the effect that can outweigh gravity darkening of the inner end of the ellipsoid, is increased distortion of the red giant at periastron.

Due to small periastron separations resulting from highly eccentric orbits, at periastron the greater influence of the companion causes the red giant to become more distorted, its ellipsoidal shape more pronounced. As the major axis of the ellipsoid lengthens and the minor axes contract, the apparent surface area of the ellipsoid

seen ‘side-on’ increases, and its apparent surface area seen ‘end-on’ decreases. Since the light maxima of ellipsoidal variables correspond to observing the star side-on, the increased apparent surface area means higher observed flux, so the maximum closest to periastron is brighter. Similarly, light minima are seen when the ellipsoid is end-on, and a decreased apparent surface area means lower observed flux, so the minimum nearest periastron is dimmer than the alternate minimum.

This distortion effect would naturally become more pronounced with eccentricity, and be less apparent for circular or low eccentricity orbits. Its phase placement, and whether it affects a minimum or a maximum, or both equally, depends on where in the orbit periastron occurs, i.e. on the angle of periastron. As an example, OGLE052438.40 has the lowest eccentricity of the current sample and shows nearly equal light maxima as periastron occurs closest to the deep minimum, although its eccentricity of 0.14 is enough for the distortion effect to result in a deeper minimum at inferior conjunction than at superior. However, for the nearly circular orbits of the ellipsoidal variables in the Nicholls et al. (2010) sample, the maxima are equal and the deeper minimum is purely due to gravity darkening and is found, as expected, at superior conjunction.

#### 5.4.2 Maintaining Eccentricity in Evolved Close Binaries

The increased distortion of the red giant at periastron observed in eccentric ellipsoidal variables, and described above, shows that a small star can significantly affect the shape of a much larger binary companion on timescales shorter than the orbital period. We showed in Nicholls et al. (2010) that sequence E binaries generally show no evidence of a mid-infrared excess that would indicate enhanced circumstellar or circumbinary dust. Thus, there is no observed evidence for mass loss from these binary systems. However, mass transfer between the components cannot be ruled out.

By modelling eccentric ellipsoidal red giant binaries, we have determined complete orbital solutions for these poorly understood stars. Our results can serve as input for future modelling to determine how eccentricity is maintained in these stars, and in other evolved eccentric binaries, possibly by mass transfer.

### 5.5 Conclusions

We have confirmed that ellipsoidal red giant binaries with unusual light curve shapes are in eccentric orbits, and we have used the Wilson–Devinney code to model the orbits and obtain orbital and stellar parameters, including masses of the stars. We find ellipsoidal variables that do not display eclipses are generally at high orbital inclinations, although edge-on orbits amongst intermediate-mass non-eclipsing ellipsoidal variables are rare. Unlike their counterparts in circular orbits, eccentric ellipsoidal variables generally have unequal maxima as well as minima in their light curves, often with one maximum spanning a significantly narrower phase and the deeper minimum occurring at inferior conjunction, instead of at superior conjunction as gravity darkening would dictate. We suggested that these phenomena are due to

greater distortion of the ellipsoidal red giant at periastron due to the high eccentricities. By determining the properties of eccentric sequence E stars we have laid the groundwork for future modelling to determine how the eccentricity is maintained in these stars.

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# Conclusions

Here we draw together the results obtained in this study of the lesser-known red giant variables, and comment on possible future investigations.

## 6.1 Long Secondary Period Variables

This study presents the largest sample of LSPVs with radial velocity curves that has been published to date. Our results confirm those of Hinkle et al. (2002) and Wood et al. (2004), that the velocity curves generally show a typical shape with a swifter increase than decrease, and that the full velocity amplitudes are all approximately a few  $\text{km s}^{-1}$ . Our analysis discovered for the first time that the LSP light and velocity curves are offset by a phase of 0.25, with minimum light generally occurring at mean rising velocity, and that LSP light and velocity amplitudes are not correlated.

We were able to make particular comment on the two most popular models for LSP origin, radial pulsation and binarity. In terms of radial pulsation, the insoluble problem is the enormous radius variation we calculate, when we assume that the observed radial velocity represents pulsation, compared to the small light and  $T_{\text{eff}}$  amplitudes of LSPVs. The typical radius change is  $\sim 30\%$  over the full cycle of one LSP, an amplitude only seen in Mira variables, where it is accompanied by much larger light amplitudes than those of the LSPVs.

For the binary model, the characteristic velocity curve shape and its small amplitude are inexplicable. The common velocity curve shapes result in a distribution of angle of periastron that is biased towards values larger than  $180^\circ$ . A selection effect that could produce this distribution among binaries is unlikely. The small velocity amplitudes imply companions of very low mass ( $\sim 0.09 M_\odot$ ), and their similarity is difficult to explain. Statistical studies (Grether & Lineweaver, 2006) have shown systems with companions at this mass comprise a very small percentage of binaries, and it is unclear why the masses should not be more uniformly distributed.

LSPVs show a significant mid-IR excess when compared to variable red giants without LSPs. Although previous studies found no evidence of an IR excess in LSPVs, the new IR surveys undertaken by the Spitzer telescope provide larger and more accurate samples. The observed mid-IR excess indicates that the LSP is associated with enhanced circumstellar dust. Further to this, we noticed that in the  $(K - [24], J - K)$  plane LSPVs lie between variables with spherical dust shells and stars with dusty disks. From this we conclude that the dust around LSPVs is either

in a disk or some other clumpy, nonspherical configuration. Whether this dust is a cause or an effect of the LSP we are unable to say.

Despite the fact that we are unable to provide a convincing model for the cause of the LSP, our investigation has shed new light on this decades-old mystery. By analysing the light and velocity curves, and the mid-IR excess, we have been able to impose new constraints on models for LSP origin.

### 6.1.1 Future work

In addition to the results presented here, we have pursued other avenues of LSPV investigation. Spectropolarimetric observations of nearby LSPVs rule out large-scale magnetic activity which could indicate star spots (Wood et al., 2009). Optical interferometry could show any distortion of LSPVs caused by e.g. nonradial pulsation. We have been seeking VLTI MIDI and AMBER data for nearby LSPVs. The small amount of VLTI data taken to date shows evidence for asymmetries, but there is insufficient baseline data for imaging. We hope our future applications will lead to more definitive results.

Lagadec et al. (2009) show how mid-IR spectra and dust model fits can be used to examine dust species, temperature, distance from the star, and dust mass loss rates. Mid-IR spectra of LSPVs do not currently exist, but this data could provide a wealth of information about the circumstellar matter of these stars, and how it relates to the LSP.

While further observations may prove instrumental in determining the LSP cause, we believe theory will play an important part in solving this mystery.

Wood et al. (2004) noted that nonradial pulsation could be a likely LSP cause, if the radiative layers of red giants are significantly thicker than current models suggest. Other authors (e.g. Stothers, 2010) have suggested that convection could play a role in causing the observed LSP variations.

We expect that the path to the LSP solution will be clearer when 3D stellar models become easy to compute. Three-dimensional models of convection in particular may hold the key to a better understanding of AGB atmospheres, and perhaps with them the elusive cause of the LSP.

## 6.2 Ellipsoidal Red Giant Binaries

We have presented the first unambiguous evidence that the red giant binaries lying on sequence E are ellipsoidal variables, showing a doubling of their light curves with respect to their radial velocity curves. We find that for variables with small eccentricity, the deeper of the two light curve minima lies at superior conjunction, and is most likely a result of gravity darkening. We find no evidence of a mid-IR excess associated with these ellipsoidal red giant binaries, indicating no enhanced levels of circumstellar dust.

In comparing the light and radial velocity curves of both sequence E stars and LSPVs, we were able to show that the LSP variation is not caused by ellipsoidal

variability, and to demonstrate the huge disparity between the properties of LSPVs and sequence E stars.

We have confirmed that the unusual light curve shapes observed by Soszyński et al. (2004) in  $\sim 10\%$  of sequence E stars do indeed represent eccentric orbits, and have analysed the light and radial velocity curves for a sample of these eccentric ellipsoidal variables. We find that many have light curves with unequal maxima as well as minima, experience their deeper light minimum at inferior conjunction (not superior conjunction, as predicted by gravity darkening), and have parts of their light curve stretched or squashed in phase. We propose that these phenomena are due to the increased influence of the companion at periastron in a highly eccentric orbit, causing a greater distortion of the ellipsoidal red giant.

We have used the Wilson–Devinney code to model the light and velocity curves of a sample of eccentric sequence E stars, and to obtain their system parameters. Our results provide a basis for future modelling to determine how a significant eccentricity can be maintained in such evolved systems.

### 6.2.1 Future work

The question of how eccentricity is maintained in the diverse collection of evolved binaries with non-circular orbits remains unsolved. Our determination of the system parameters of eccentric sequence E stars provides a starting point for detailed modelling to discern the plausibility of each of the proposed mechanisms. SPH models of enhanced mass transfer at periastron, for example (as proposed by Soker, 2000), may be able to show whether the amount of mass transferred is enough to maintain the eccentricities observed in these eccentric ellipsoidal variables and in other evolved binaries.

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## Calculating L and $T_{\text{eff}}$ from Photometry

The luminosity was calculated from the MACHO Red photometry. The MACHO Red ( $M_R$ , effective wavelength 5400 Å) and Blue ( $M_B$ , effective wavelength 7200 Å) magnitudes were first dereddened using a colour excess of  $E(B - V) = 0.08$  for the LMC (Keller & Wood, 2006) and absorption  $A(\lambda)$  calculated by the reddening law from Cardelli et al. (1989). This gave  $A(M_B) = 0.2531$  and  $A(M_R) = 0.1783$ .

The bolometric correction to  $M_{R_0}$  (where the zero subscript denotes dereddened values) was derived through the following process. Note that we excluded the carbon stars in this procedure since the available calibrations are for M stars only. First the bolometric correction to  $V_0$  was calculated, using a calibration derived from the data of Fluks et al. (1994):

$$BC_V = 0.662 - 0.872(V - I)_0 - 0.128(V - I)_0^2, \quad (\text{A.1})$$

for  $1 < (V - I)_0 < 4$ . The colour was converted from  $(M_B - M_R)_0$  to  $(V - I)_0$  using the equation

$$(V - I)_0 = \frac{M_{B_0} - M_{R_0} - 0.120}{0.625}$$

which was derived from MACHO magnitudes and  $V$  and  $I$  images of our field taken with the 40-inch telescope at Siding Spring Observatory, Australia. Substituting  $(V - I)_0$  in equation A.1 gave  $BC_V$ .

The bolometric correction to  $M_{B_0}$  was calculated from

$$BC_{M_B} = BC_V - (M_B - V)_0$$

where  $V_0$  was calculated using the formula

$$V_0 = M_{B_0} + 0.042 - 0.155(M_B - M_R)_0$$

derived again from the 40-inch images. From  $BC_{M_B}$  it was a simple step to calculate  $BC_{M_R}$  using

$$BC_{M_R} = BC_{M_B} - (M_R - M_B)_0,$$

the apparent bolometric magnitude was calculated from

$$m_{\text{bol}} = M_{R_0} + BC_{M_R},$$

and the absolute bolometric magnitude was calculated from

$$M_{\text{bol}} = m_{\text{bol}} - 18.54$$

taking the distance modulus as 18.54 for the LMC (from Keller & Wood, 2006).

Finally, the luminosity was calculated from

$$L = L_{\odot} \times 10^{0.4(4.75 - M_{\text{bol}})}$$

where 4.75 is the adopted absolute bolometric magnitude of the Sun.

The effective temperature was calculated from the photometry using a fit made to the stellar atmosphere derived data of Kučinskas et al. (2005) for  $[Fe/H] = -0.5$  (as appropriate for the LMC):

$$T_{\text{eff}} = \frac{3723}{((V - I)_0 - 0.8957)^{\frac{1}{7}}} \quad \text{for } (V - I)_0 > 1.2.$$

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## LSPV Radial Velocities

**Table B.1:** Heliocentric Radial Velocities of Sequence D Stars ( $\text{km s}^{-1}$ )

| HJD     | 77.7427.41 | 77.7427.72 | 77.7428.120 | 77.7428.65 | 77.7429.100 | 77.7429.47 | 77.7429.64 | 77.7430.46 | 77.7430.51 |
|---------|------------|------------|-------------|------------|-------------|------------|------------|------------|------------|
| 2954.85 | 240.85     | 273.53     | 273.61      | 297.74     | 314.55      | 280.43     | 278.15     | 244.02     | 266.31     |
| 3005.86 | 239.86     | 274.41     | 272.44      | 299.37     | 313.72      | 280.73     | 277.68     | 245.33     | 265.78     |
| 3067.60 | 241.32     | 275.08     | 272.69      | 298.12     | 313.20      | 279.58     | 277.01     | 244.83     | 267.10     |
| 3091.56 | 239.64     | 271.16     | 271.76      | 298.36     | 314.18      | 279.08     | 276.49     | 244.71     | 266.76     |
| 3280.86 | 241.59     | 273.70     | 272.70      | 295.91     | 314.24      | 278.73     | -          | 241.53     | 264.68     |
| 3324.76 | 239.26     | 275.30     | 273.26      | 294.60     | 314.51      | 278.14     | -          | 240.90     | 263.61     |
| 3344.80 | 240.04     | 274.01     | 273.34      | 295.59     | 315.15      | 277.93     | -          | 242.23     | 263.88     |
| 3376.58 | 239.38     | 274.15     | 272.60      | 295.73     | 314.17      | 277.91     | -          | 243.88     | 263.67     |
| 3418.69 | 238.11     | 273.68     | 272.59      | 296.53     | 315.73      | 277.24     | -          | 244.06     | 265.99     |
| 3471.51 | 237.08     | 271.80     | 272.23      | 298.19     | 314.98      | 278.01     | -          | 243.95     | 266.41     |
| 3623.88 | -          | -          | -           | -          | -           | -          | -          | -          | -          |
| 3642.83 | 240.15     | 271.86     | 273.68      | 297.61     | 313.64      | 281.31     | -          | 242.22     | 267.86     |
| 3644.82 | 239.89     | 271.50     | 273.67      | 297.36     | 313.43      | 281.03     | -          | 241.70     | 267.60     |
| 3663.86 | 240.49     | 271.74     | 273.28      | 296.62     | 312.03      | 281.83     | -          | 241.78     | 268.17     |
| 3664.86 | 240.62     | 271.92     | 273.53      | 296.83     | 311.85      | 281.99     | -          | 241.45     | 268.16     |
| 3685.67 | 240.85     | 273.02     | 272.99      | 297.64     | 313.59      | 282.93     | -          | 240.64     | 267.92     |
| 3709.79 | 240.50     | 269.51     | 273.40      | 297.15     | 314.57      | 284.06     | -          | 242.48     | 266.48     |
| 3741.60 | 242.04     | 272.47     | 272.40      | 296.61     | 313.84      | 282.54     | -          | 243.07     | 265.69     |
| 3768.62 | 241.31     | 273.48     | 274.19      | 297.47     | 313.53      | 280.68     | -          | 242.40     | 266.54     |
| 3819.50 | 242.35     | 274.62     | 273.97      | 296.13     | 313.88      | 282.12     | -          | 245.04     | 266.56     |

**Table B.2:** Heliocentric Radial Velocities of Sequence D Stars ( $\text{km s}^{-1}$ )

| HJD     | 77.7547.34 | 77.7547.44 | 77.7547.45 | 77.7547.46 | 77.7549.42 | 77.7549.46 | 77.7549.98 | 77.7550.37 | 77.7550.43 |
|---------|------------|------------|------------|------------|------------|------------|------------|------------|------------|
| 2954.85 | -          | 271.67     | 285.35     | 288.07     | 264.07     | 260.73     | 252.15     | 268.63     | 246.81     |
| 3005.86 | -          | 272.77     | 284.58     | 288.83     | 265.34     | 263.77     | 250.87     | 268.39     | 245.52     |
| 3067.60 | -          | 274.35     | 285.09     | 286.59     | 265.71     | 259.73     | 250.15     | 266.78     | 246.14     |
| 3091.56 | -          | 273.94     | 283.22     | 289.78     | 264.54     | 261.23     | 250.59     | 263.95     | 245.54     |
| 3280.86 | 245.73     | 271.42     | 285.72     | 285.62     | 263.97     | 265.46     | 247.66     | 268.93     | 243.23     |
| 3324.76 | 245.85     | 271.33     | 286.04     | 287.17     | 265.80     | 264.00     | 248.92     | 268.80     | 242.12     |
| 3344.80 | 245.87     | 269.51     | 285.40     | 286.96     | 266.58     | 264.24     | 247.47     | 269.10     | 242.80     |
| 3376.58 | 247.98     | 271.53     | 286.18     | 287.76     | 261.69     | 265.33     | 248.53     | 268.73     | 243.15     |
| 3418.69 | 248.83     | 269.10     | 285.27     | 289.41     | 264.91     | 264.05     | 249.77     | 266.61     | 244.73     |
| 3471.51 | 246.93     | 268.16     | 283.63     | 288.30     | 263.55     | 265.24     | 251.02     | 266.85     | 245.47     |
| 3623.88 | -          | -          | -          | -          | -          | -          | -          | -          | -          |
| 3642.83 | 248.68     | 269.90     | 286.33     | 289.53     | -          | 263.93     | 250.45     | 270.00     | -          |
| 3644.82 | 248.95     | 269.72     | 285.88     | 288.96     | 263.56     | 263.49     | 250.20     | 269.72     | 242.83     |
| 3663.86 | 248.53     | 271.56     | 286.36     | 288.87     | 263.10     | 263.33     | 251.04     | 270.13     | 243.73     |
| 3664.86 | 248.85     | 271.41     | 286.45     | 288.31     | 263.08     | 263.46     | 251.24     | 270.05     | 243.81     |
| 3685.67 | 249.90     | 270.00     | 288.68     | 288.59     | 262.46     | 261.69     | 250.16     | 271.57     | 243.77     |
| 3709.79 | 250.89     | 270.49     | 286.38     | 287.98     | 262.27     | 261.44     | 250.74     | 273.17     | 242.65     |
| 3741.60 | 250.26     | 271.20     | 287.12     | 284.94     | 263.84     | 262.95     | 249.77     | 270.49     | 242.79     |
| 3768.62 | 250.74     | 272.10     | 287.26     | 286.68     | 266.00     | 263.09     | 247.74     | 270.33     | 242.54     |
| 3819.50 | 247.80     | 271.75     | 286.39     | 287.37     | 266.08     | 262.80     | 247.37     | 268.62     | 243.97     |

**Table B.3:** Heliocentric Radial Velocities of Sequence D Stars ( $\text{km s}^{-1}$ )

| HJD     | 77.7550.44 | 77.7551.20 | 77.7551.26 | 77.7552.111 | 77.7667.918 | 77.7669.1027 | 77.7669.1028 | 77.7669.973 | 77.7669.974 |
|---------|------------|------------|------------|-------------|-------------|--------------|--------------|-------------|-------------|
| 2954.85 | 249.43     | 250.75     | 286.10     | 271.38      | 262.37      | 270.99       | 222.05       | 272.70      | 285.44      |
| 3005.86 | 247.88     | 250.69     | 285.55     | 270.24      | 262.20      | 267.56       | 221.26       | 271.71      | 285.20      |
| 3067.60 | 246.83     | 250.30     | 287.32     | 271.98      | 261.98      | 267.17       | 220.02       | 271.43      | 285.20      |
| 3091.56 | 246.53     | 250.67     | 286.09     | 273.46      | 262.54      | 265.10       | 220.66       | 270.38      | 286.83      |
| 3280.86 | 247.89     | 249.27     | 285.40     | 276.34      | 261.99      | 270.07       | 219.32       | 273.92      | -           |
| 3324.76 | 249.77     | 249.29     | 286.44     | 270.97      | 262.21      | 268.14       | 219.05       | 270.69      | -           |
| 3344.80 | 249.62     | 248.27     | 286.06     | 271.61      | 263.53      | 268.00       | 219.89       | 272.26      | -           |
| 3376.58 | 250.10     | 249.86     | 287.12     | 274.78      | 261.37      | 265.60       | 221.26       | 271.15      | -           |
| 3418.69 | 248.39     | 249.30     | 287.18     | 269.93      | 261.34      | 266.14       | 221.65       | 270.15      | -           |
| 3471.51 | 247.71     | 250.68     | 286.26     | 271.14      | 255.78      | 272.16       | 221.19       | 271.50      | -           |
| 3623.88 | -          | -          | -          | -           | -           | -            | -            | -           | -           |
| 3642.83 | 246.66     | 248.33     | 284.60     | 274.91      | 263.41      | 266.07       | 220.65       | 273.99      | -           |
| 3644.82 | 246.41     | 248.05     | 284.53     | 274.28      | 262.79      | 265.72       | 220.03       | 273.74      | -           |
| 3663.86 | 247.87     | 249.67     | 286.85     | 273.23      | 262.07      | 265.81       | 220.20       | 272.82      | -           |
| 3664.86 | 247.83     | 249.63     | 287.10     | 273.68      | 261.66      | 265.89       | 220.23       | 272.78      | -           |
| 3685.67 | 248.45     | 250.19     | 285.08     | 274.49      | 261.43      | 267.55       | 221.18       | 272.65      | -           |
| 3709.79 | 248.12     | 249.63     | 286.42     | 275.24      | 261.56      | 271.28       | 219.85       | 272.80      | -           |
| 3741.60 | 249.23     | 251.43     | 285.98     | 274.35      | 260.44      | 274.26       | 220.69       | 271.41      | -           |
| 3768.62 | 248.75     | 250.37     | 287.37     | 273.59      | 259.74      | 271.39       | 217.63       | 271.57      | -           |
| 3819.50 | 248.55     | 249.74     | 288.28     | 273.15      | 258.39      | 270.38       | 218.62       | 271.67      | -           |



**Table B.4:** Heliocentric Radial Velocities of Sequence D Stars ( $\text{km s}^{-1}$ )

| HJD     | 77.7669.991 | 77.7670.39 | 77.7670.934 | 77.7671.282 | 77.7672.38 | 77.7673.25 | 77.7789.42 | 77.7789.51 | 77.7789.54 |
|---------|-------------|------------|-------------|-------------|------------|------------|------------|------------|------------|
| 2954.85 | 303.26      | 261.01     | 246.01      | 238.28      | 253.38     | 253.46     | 276.23     | 236.55     | 280.43     |
| 3005.86 | 302.67      | 259.39     | 245.85      | 238.80      | 253.20     | 253.79     | 276.19     | 238.26     | 283.64     |
| 3067.60 | 302.16      | 264.37     | 247.95      | 237.69      | 250.50     | 253.83     | 278.85     | 240.19     | 283.25     |
| 3091.56 | 300.66      | 264.74     | 248.12      | 238.73      | 249.94     | 253.30     | 280.54     | 239.21     | 283.05     |
| 3280.86 | 302.96      | 265.46     | 247.85      | 239.67      | 253.98     | 250.53     | 283.00     | 239.04     | 282.95     |
| 3324.76 | 301.13      | 264.32     | 248.55      | 240.63      | 255.52     | 255.11     | 281.37     | 237.79     | 284.01     |
| 3344.80 | 301.27      | 263.56     | 245.72      | 239.50      | 254.59     | 253.68     | 278.96     | 236.64     | 283.23     |
| 3376.58 | 303.24      | 264.54     | 245.75      | 239.82      | 255.17     | 254.97     | 279.73     | 238.36     | 282.15     |
| 3418.69 | 303.99      | 262.08     | 245.21      | 240.80      | 254.18     | 253.40     | 282.92     | 239.12     | 283.08     |
| 3471.51 | 302.01      | 262.20     | 246.61      | 241.03      | 254.19     | 252.98     | 278.77     | 239.50     | 282.05     |
| 3623.88 | -           | -          | -           | 241.95      | -          | -          | -          | -          | -          |
| 3642.83 | 303.30      | 261.12     | 249.28      | 241.81      | 252.35     | 249.63     | 280.78     | 239.70     | 283.12     |
| 3644.82 | 302.58      | 260.92     | 249.06      | 241.32      | 251.94     | 249.43     | 280.26     | 239.46     | 282.80     |
| 3663.86 | 303.74      | 262.11     | 247.78      | 240.26      | 252.15     | 251.56     | 279.39     | 238.94     | 283.95     |
| 3664.86 | 303.84      | 262.27     | 247.84      | 240.27      | 252.23     | 251.02     | 279.22     | 239.43     | 284.19     |
| 3685.67 | 303.28      | 262.86     | 248.49      | 239.27      | 250.93     | 251.63     | 278.17     | 240.08     | 283.44     |
| 3709.79 | 303.06      | 262.94     | 249.99      | 240.06      | 251.15     | 252.61     | 279.70     | 239.39     | 281.66     |
| 3741.60 | 303.75      | 262.08     | 247.45      | 240.67      | 250.78     | 254.54     | 280.79     | 240.23     | 281.03     |
| 3768.62 | 302.45      | 262.85     | 248.09      | 238.77      | 249.28     | 255.43     | 279.24     | 239.96     | 285.05     |
| 3819.50 | 301.15      | 261.08     | 248.07      | 239.40      | 250.91     | 254.03     | 279.04     | 238.24     | 283.97     |

**Table B.5:** Heliocentric Radial Velocities of Sequence D Stars ( $\text{km s}^{-1}$ )

| HJD     | 77.7790.50 | 77.7791.53 | 77.7793.38 | 77.7794.13 | 77.7910.50 | 77.7910.59 | 77.7911.22 | 77.7911.29 | 77.7912.33 |
|---------|------------|------------|------------|------------|------------|------------|------------|------------|------------|
| 2954.85 | 225.81     | -          | 266.45     | -          | 262.04     | 318.14     | 224.64     | 264.45     | 322.26     |
| 3005.86 | 228.20     | -          | 266.01     | -          | 261.84     | 318.63     | 223.68     | 266.40     | 322.76     |
| 3067.60 | 228.92     | -          | 267.08     | -          | 261.13     | 317.78     | 221.67     | 267.11     | 318.95     |
| 3091.56 | 228.94     | -          | 267.45     | -          | 260.77     | 317.15     | 221.72     | 271.79     | 321.38     |
| 3280.86 | -          | 242.02     | 267.21     | 234.80     | 262.02     | 321.77     | 224.86     | 264.13     | 323.15     |
| 3324.76 | -          | 243.54     | 266.79     | 235.89     | 262.20     | 320.79     | 225.02     | 265.92     | 322.22     |
| 3344.80 | -          | 244.16     | 268.20     | 235.82     | 262.58     | 319.71     | 225.35     | 266.84     | 321.84     |
| 3376.58 | -          | 244.80     | 267.03     | 236.07     | 263.02     | 320.57     | 226.03     | 266.85     | 320.90     |
| 3418.69 | -          | 243.47     | 266.97     | 237.04     | 262.20     | 319.49     | 222.81     | 267.55     | 321.22     |
| 3471.51 | -          | 243.58     | 267.67     | 238.33     | 262.54     | 318.81     | 223.78     | 268.82     | 323.44     |
| 3623.88 | -          | 243.33     | -          | -          | -          | -          | -          | -          | -          |
| 3642.83 | -          | 244.73     | 267.85     | 237.90     | 260.21     | 319.84     | 225.58     | 265.25     | 322.12     |
| 3644.82 | -          | 244.23     | 267.52     | 237.44     | 259.74     | 319.87     | 225.25     | 265.03     | 321.03     |
| 3663.86 | -          | 242.74     | 268.19     | 237.87     | 259.14     | 319.40     | 223.91     | 265.44     | 321.45     |
| 3664.86 | -          | 242.76     | 268.42     | 238.10     | 259.17     | 319.62     | 224.40     | 266.36     | 322.21     |
| 3685.67 | -          | 243.68     | 267.64     | 238.80     | 259.21     | 320.88     | 225.42     | 266.77     | 321.53     |
| 3709.79 | -          | 243.72     | 269.37     | 240.32     | 261.13     | 321.67     | 224.90     | 265.98     | 322.04     |
| 3741.60 | -          | 241.87     | 268.12     | 238.80     | 261.98     | 320.69     | 223.31     | 269.26     | 321.26     |
| 3768.62 | -          | 244.38     | 268.39     | 236.10     | 264.18     | 318.66     | 225.39     | 265.78     | 321.81     |
| 3819.50 | -          | 243.37     | 268.99     | 238.56     | -          | -          | 224.58     | 264.83     | 323.58     |

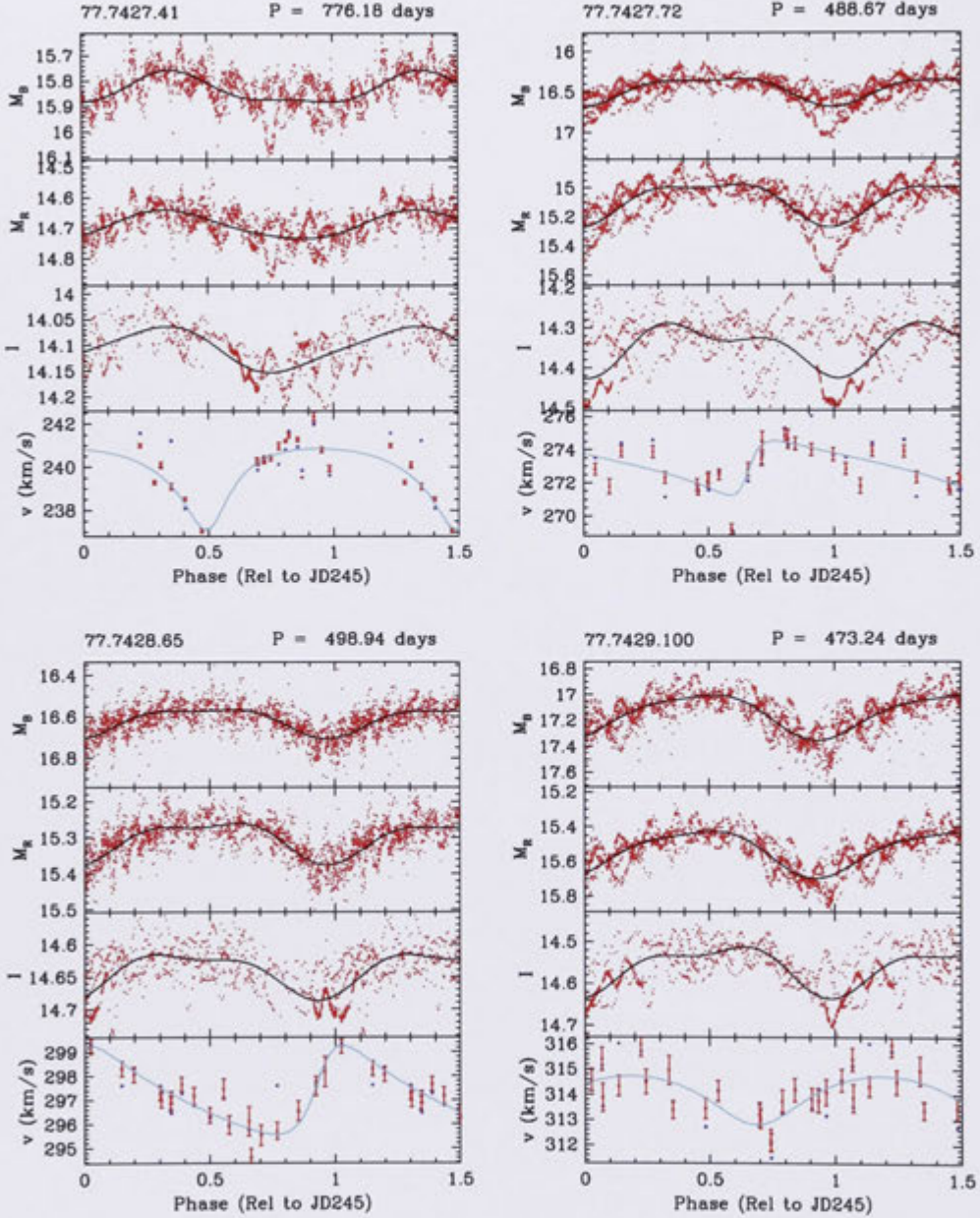
**Table B.6:** Heliocentric Radial Velocities of Sequence D Stars ( $\text{km s}^{-1}$ )

| HJD     | 77.7912.36 | 77.7912.66 | 77.7913.403 | 77.7914.39 | 77.7914.51 | 77.7914.60 | 77.8032.46 | 77.8032.54 | 77.8033.33 |
|---------|------------|------------|-------------|------------|------------|------------|------------|------------|------------|
| 2954.85 | 300.32     | 264.69     | 224.41      | 240.34     | 263.30     | 297.74     | 286.39     | 266.71     | 310.61     |
| 3005.86 | 299.41     | 264.39     | 223.21      | 238.21     | 263.39     | 297.24     | 285.51     | 269.53     | 312.47     |
| 3067.60 | 299.31     | 265.70     | 222.63      | 238.56     | 264.10     | 293.97     | 284.85     | 269.37     | 312.03     |
| 3091.56 | 299.54     | 266.15     | 222.78      | 236.91     | 264.44     | 245.80     | 284.81     | 268.77     | 311.31     |
| 3280.86 | 301.54     | 263.84     | 223.42      | 236.10     | 264.26     | 298.62     | 283.88     | -          | 311.65     |
| 3324.76 | 300.44     | 265.23     | 222.43      | 235.63     | 262.86     | 296.59     | 282.34     | -          | 311.71     |
| 3344.80 | 300.36     | 264.65     | 222.64      | 235.23     | 263.71     | 293.45     | 285.70     | -          | 312.13     |
| 3376.58 | 300.24     | 265.02     | 222.54      | 236.11     | 262.33     | 296.09     | 284.25     | -          | 311.25     |
| 3418.69 | 300.68     | 266.51     | 223.60      | 236.76     | 263.03     | 296.11     | 285.14     | -          | 312.24     |
| 3471.51 | 300.06     | 265.94     | 222.13      | 237.23     | 263.52     | 249.40     | 285.18     | -          | 312.55     |
| 3623.88 | -          | -          | -           | -          | -          | 251.44     | -          | -          | -          |
| 3642.83 | 298.55     | 263.46     | 222.14      | 240.93     | 264.30     | 296.09     | 284.04     | -          | 312.27     |
| 3644.82 | 298.18     | 264.24     | 221.79      | 240.58     | 263.69     | 296.37     | 283.99     | -          | 312.11     |
| 3663.86 | 299.61     | 264.07     | 221.18      | 240.60     | 265.11     | 296.34     | 284.66     | -          | 311.55     |
| 3664.86 | 299.73     | 263.57     | 221.42      | 240.28     | 265.44     | 296.03     | 284.41     | -          | 311.90     |
| 3685.67 | 301.09     | 263.62     | 222.58      | 236.38     | 264.46     | 298.20     | 285.21     | -          | 312.00     |
| 3709.79 | 301.45     | 264.97     | 222.20      | 237.61     | 265.67     | 248.17     | 283.21     | -          | 312.40     |
| 3741.60 | 300.65     | 264.50     | 222.24      | 239.87     | 264.42     | 298.68     | 283.58     | -          | 311.63     |
| 3768.62 | 302.35     | 265.65     | 222.55      | 238.74     | 263.08     | 251.34     | 283.13     | -          | 311.79     |
| 3819.50 | 302.07     | 265.65     | 224.61      | 237.51     | 261.03     | 253.97     | -          | -          | 312.16     |

**Table B.7:** Heliocentric Radial Velocities of Sequence D Stars ( $\text{km s}^{-1}$ )

| HJD     | 77.8033.48 | 77.8034.380 | 77.8035.48 | 77.8155.377 |
|---------|------------|-------------|------------|-------------|
| 2954.85 | 264.79     | 240.97      | 304.24     | 276.05      |
| 3005.86 | 264.47     | 238.96      | 305.20     | 274.92      |
| 3067.60 | 264.63     | 237.81      | 304.21     | 277.00      |
| 3091.56 | 265.08     | 238.24      | 304.09     | 275.35      |
| 3280.86 | 265.34     | 236.61      | 300.89     | 274.06      |
| 3324.76 | 267.17     | 237.85      | 300.54     | 274.67      |
| 3344.80 | 267.09     | 238.60      | 301.70     | 273.24      |
| 3376.58 | 267.34     | 239.58      | 300.92     | 273.29      |
| 3418.69 | 266.57     | 238.09      | 301.45     | 274.14      |
| 3471.51 | 266.34     | 237.15      | 302.33     | 275.06      |
| 3623.88 | -          | -           | -          | -           |
| 3642.83 | 266.63     | 236.33      | 303.03     | 275.44      |
| 3644.82 | 265.54     | 236.30      | 302.72     | 275.00      |
| 3663.86 | 266.76     | 234.75      | 303.97     | 275.19      |
| 3664.86 | 267.31     | 235.30      | 304.08     | 275.37      |
| 3685.67 | 267.41     | 235.83      | 306.23     | 275.09      |
| 3709.79 | 267.41     | 236.96      | 304.83     | 274.69      |
| 3741.60 | 266.64     | 236.63      | 303.03     | 274.68      |
| 3768.62 | 266.94     | 239.52      | 304.64     | 275.27      |
| 3819.50 | 266.04     | 239.10      | 303.73     | 274.97      |

# Light and Velocity Curves of LSPVs



**Figure C.1:** Light and velocity curves plotted against phase for four sequence D stars. The blue velocity points without error bars are the radial velocities without corrections and the red points with error bars are the radial velocities that have been corrected for pulsation and had specific date corrections. Also shown are the Fourier fits to the light data (black lines), and the Binary fits to the velocity data (cyan lines), both made by FITALL.



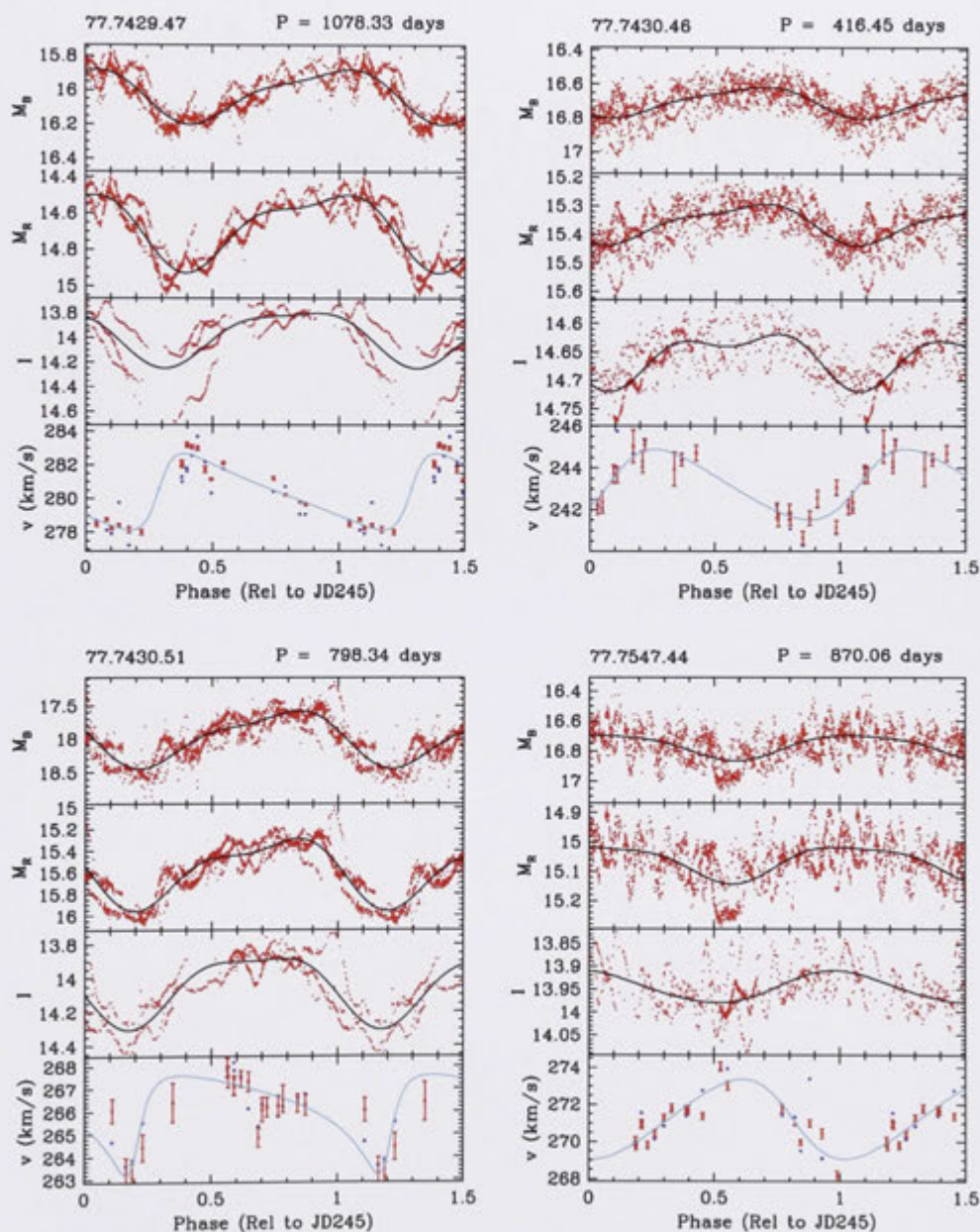


Figure C.2: Same as Figure C.1.

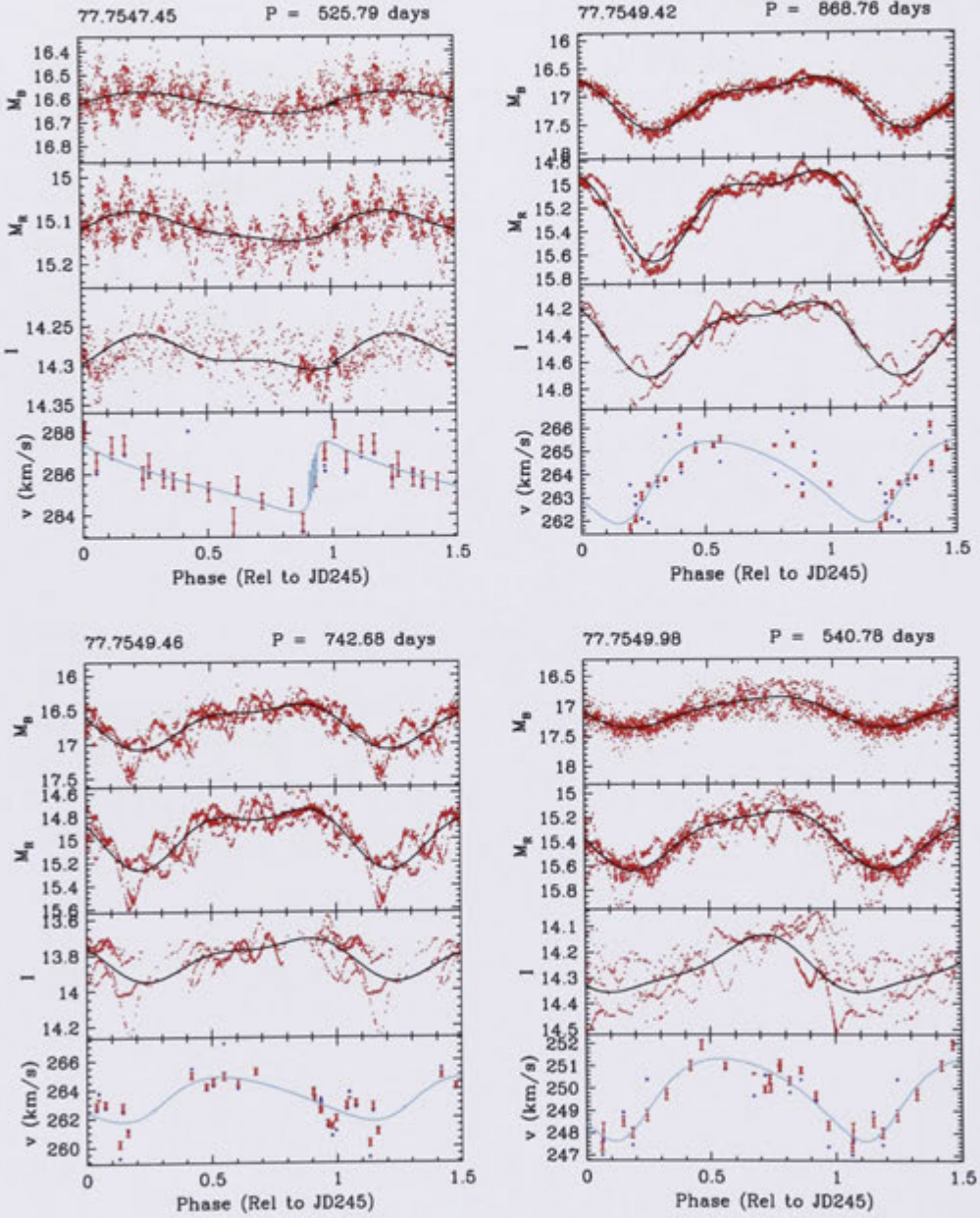


Figure C.3: Same as Figure C.1.



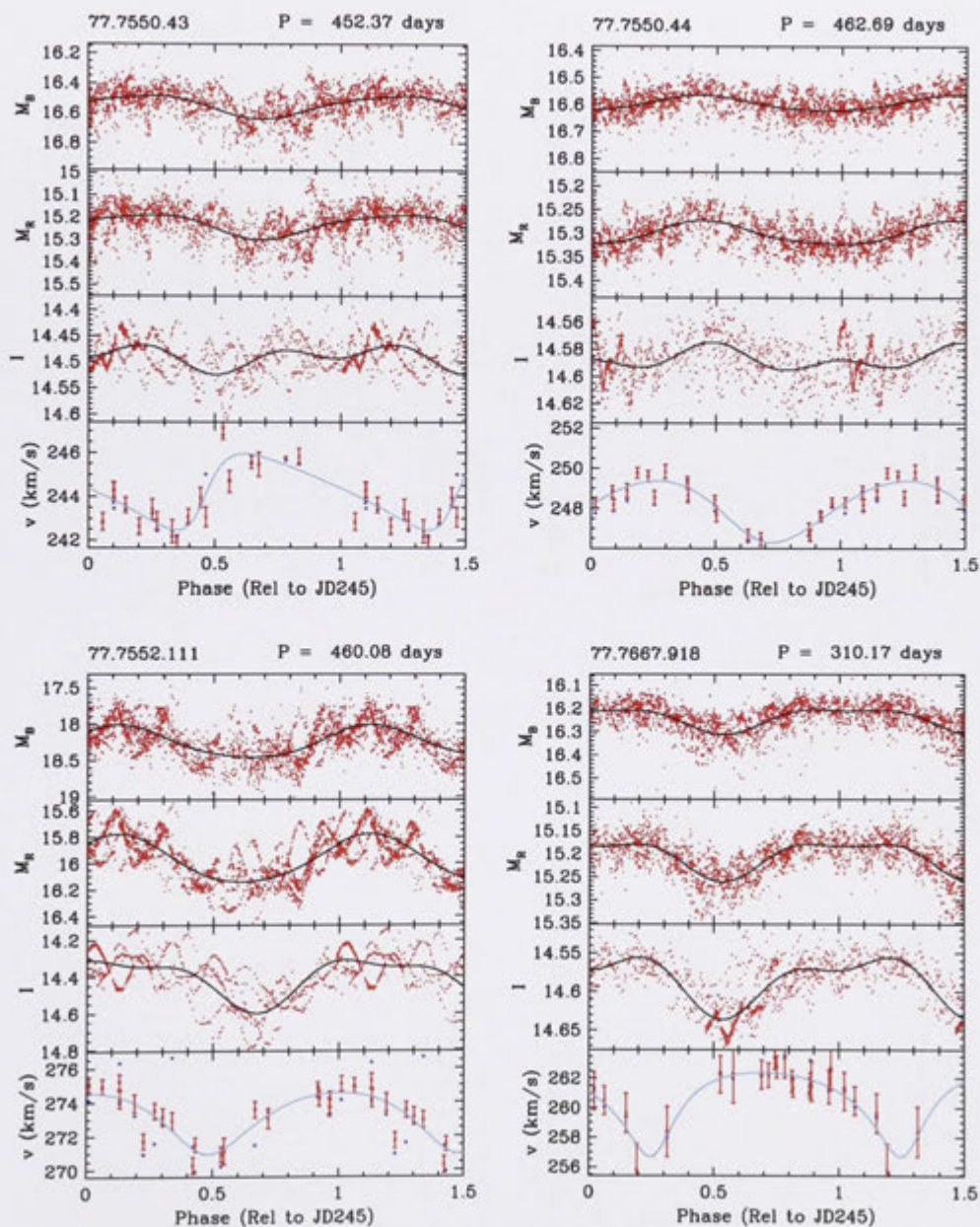


Figure C.4: Same as Figure C.1.

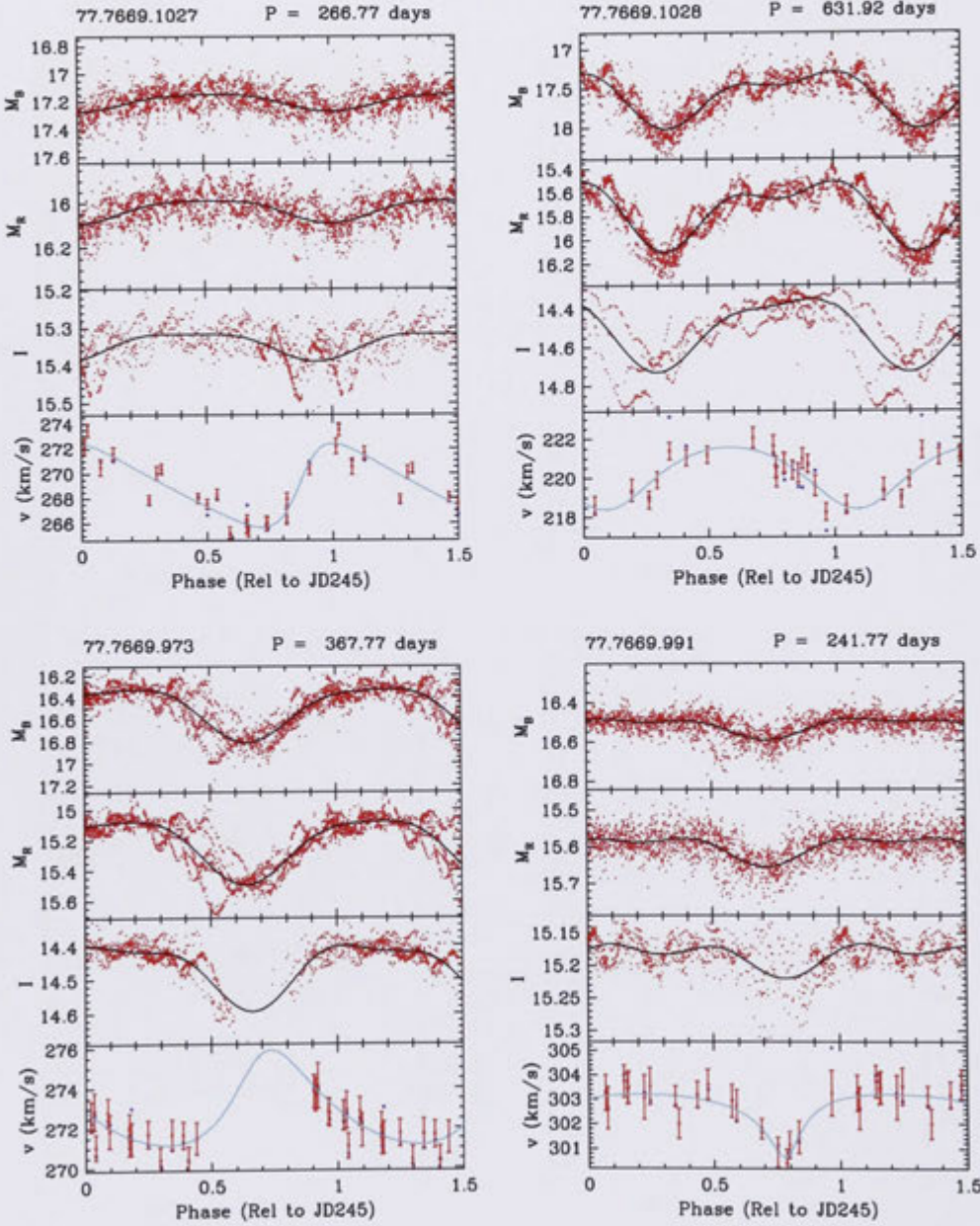


Figure C.5: Same as Figure C.1.



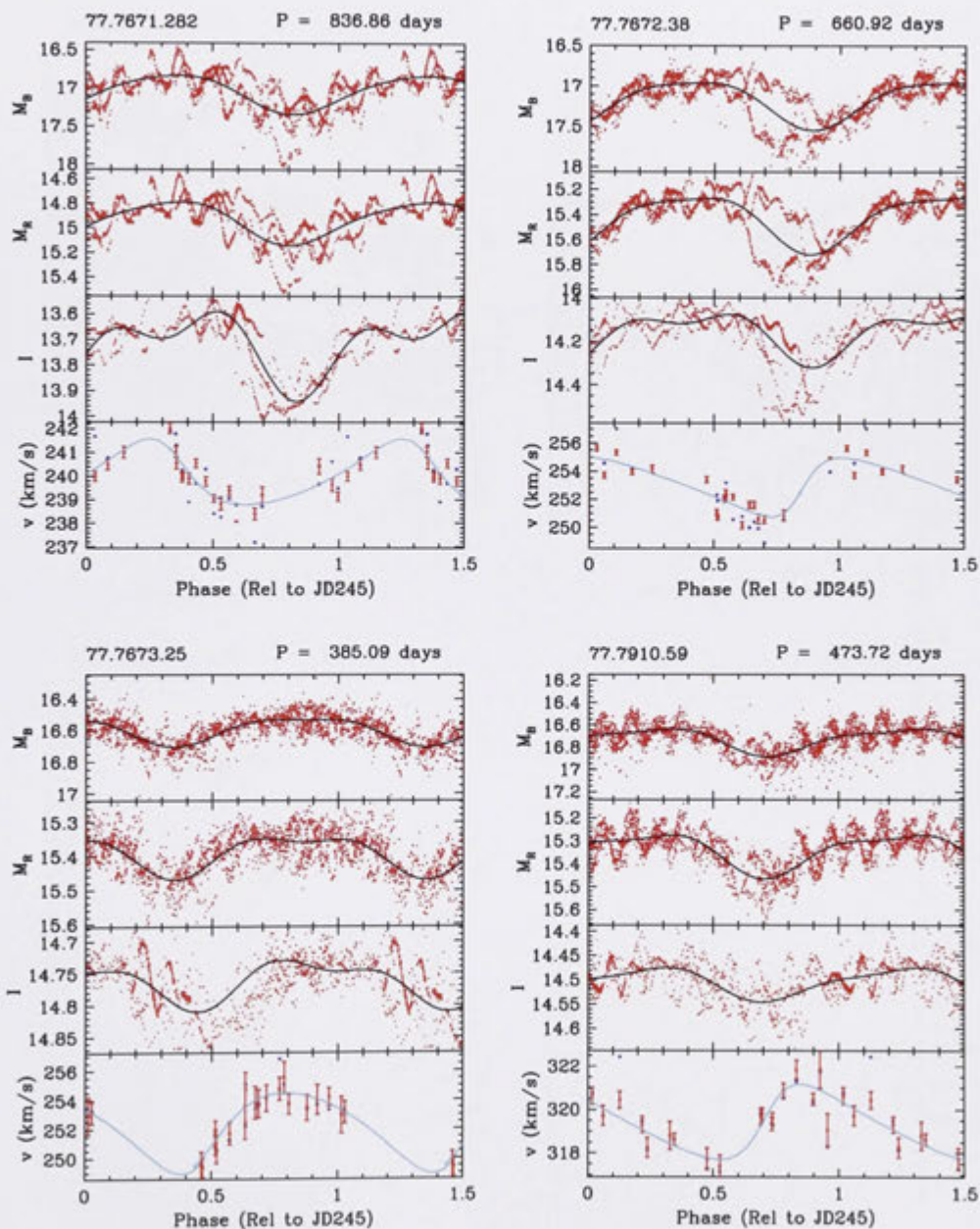


Figure C.6: Same as Figure C.1.

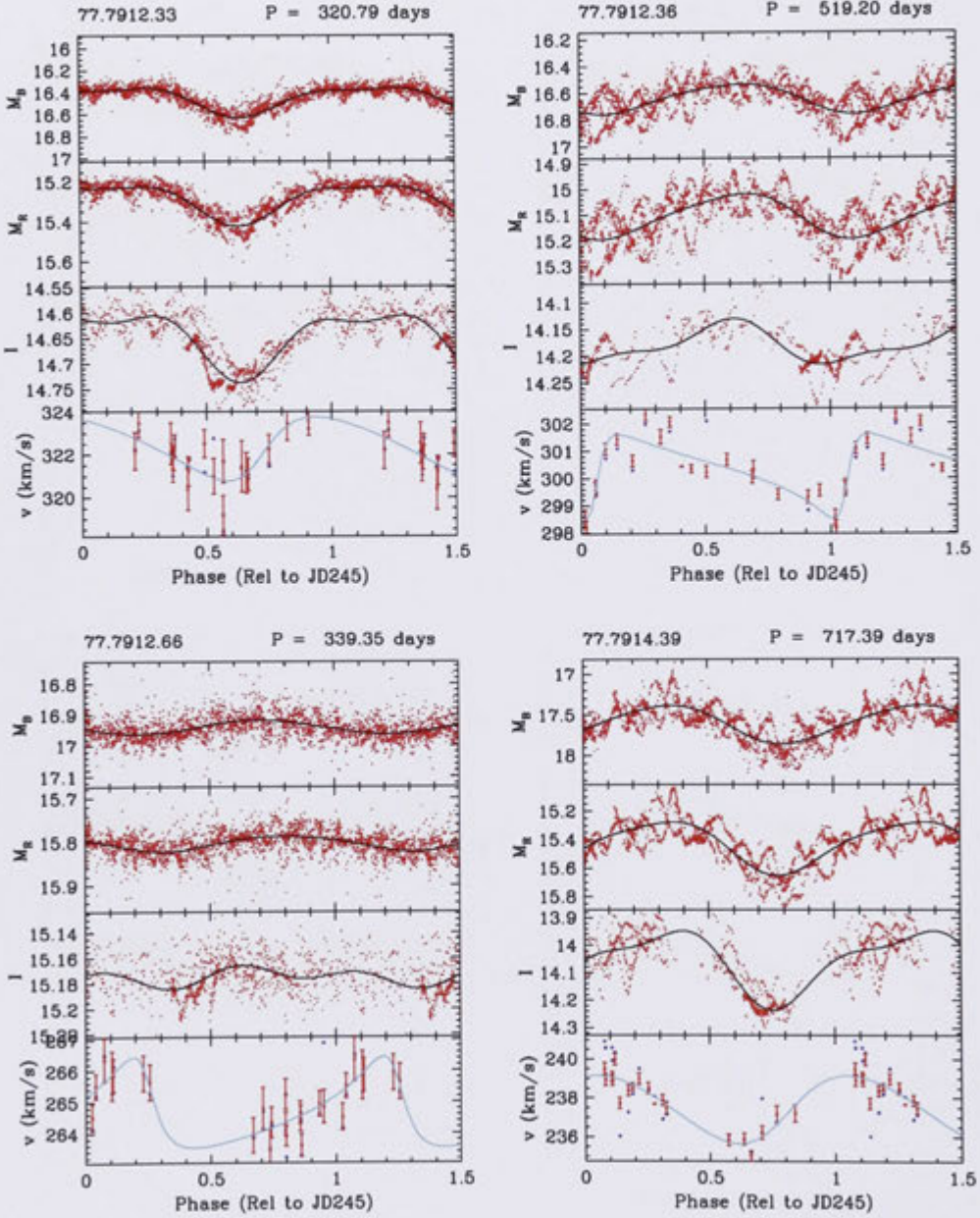


Figure C.7: Same as Figure C.1.



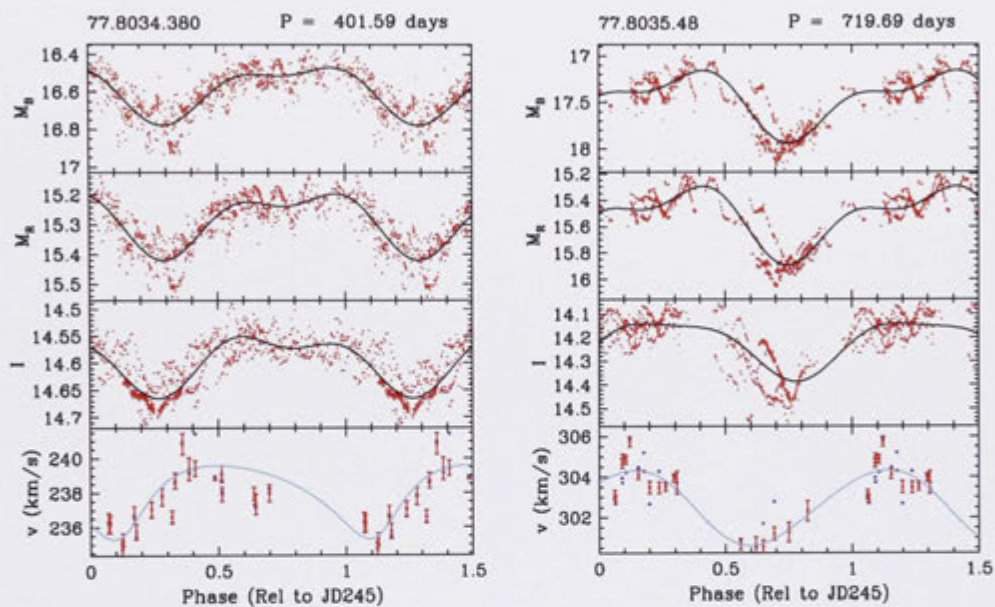
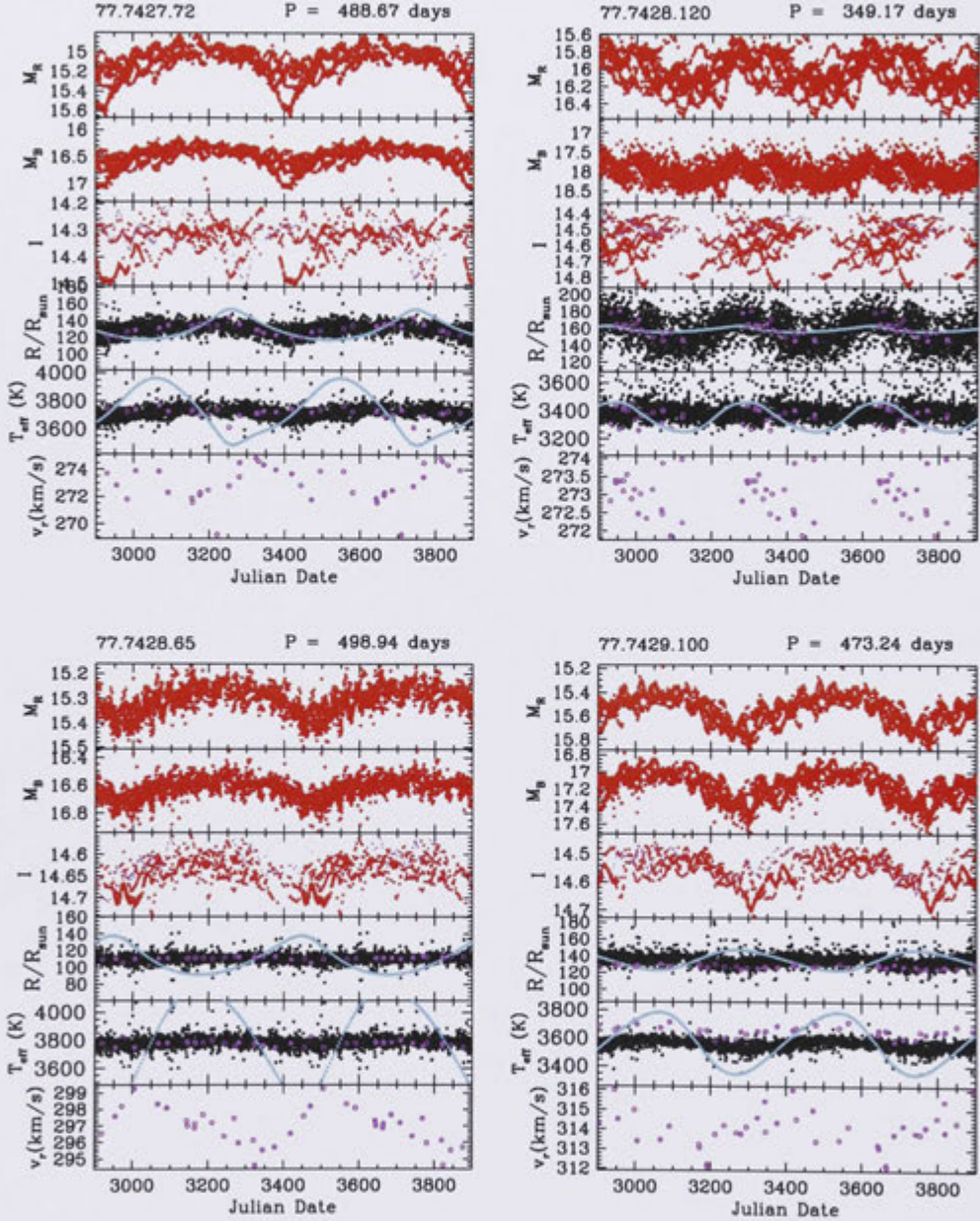


Figure C.8: Same as Figure C.1.



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## Variation of LSPV Properties



**Figure D.1:** Different properties of four typical sequence D stars plotted against Julian Date. Solid symbols denote values plotted at the date of measurement while open symbols are values that have been shifted forward or backward by one or more periods. *Top panel:* MACHO Red light curve. *Second panel:* MACHO Blue light curve. *Third panel:* OGLE  $I$  light curve. *Fourth panel:* Variation of  $R_{\text{phot}}$  (small black points), variation of  $R_{\text{vel}}$  (cyan curve) and variation of  $R_{\text{spec}}$  (large magenta points). *Fifth panel:* Variation of  $T_{\text{eff(phot)}}$  (small black points), variation of  $T_{\text{eff(spec)}}$  (large magenta points) and variation of  $T_{\text{eff(vel)}}$  (cyan curve). *Bottom panel:* Observed radial velocity. See text for details. Plots for the entire sample are available in the online version of this paper and in Appendix D.



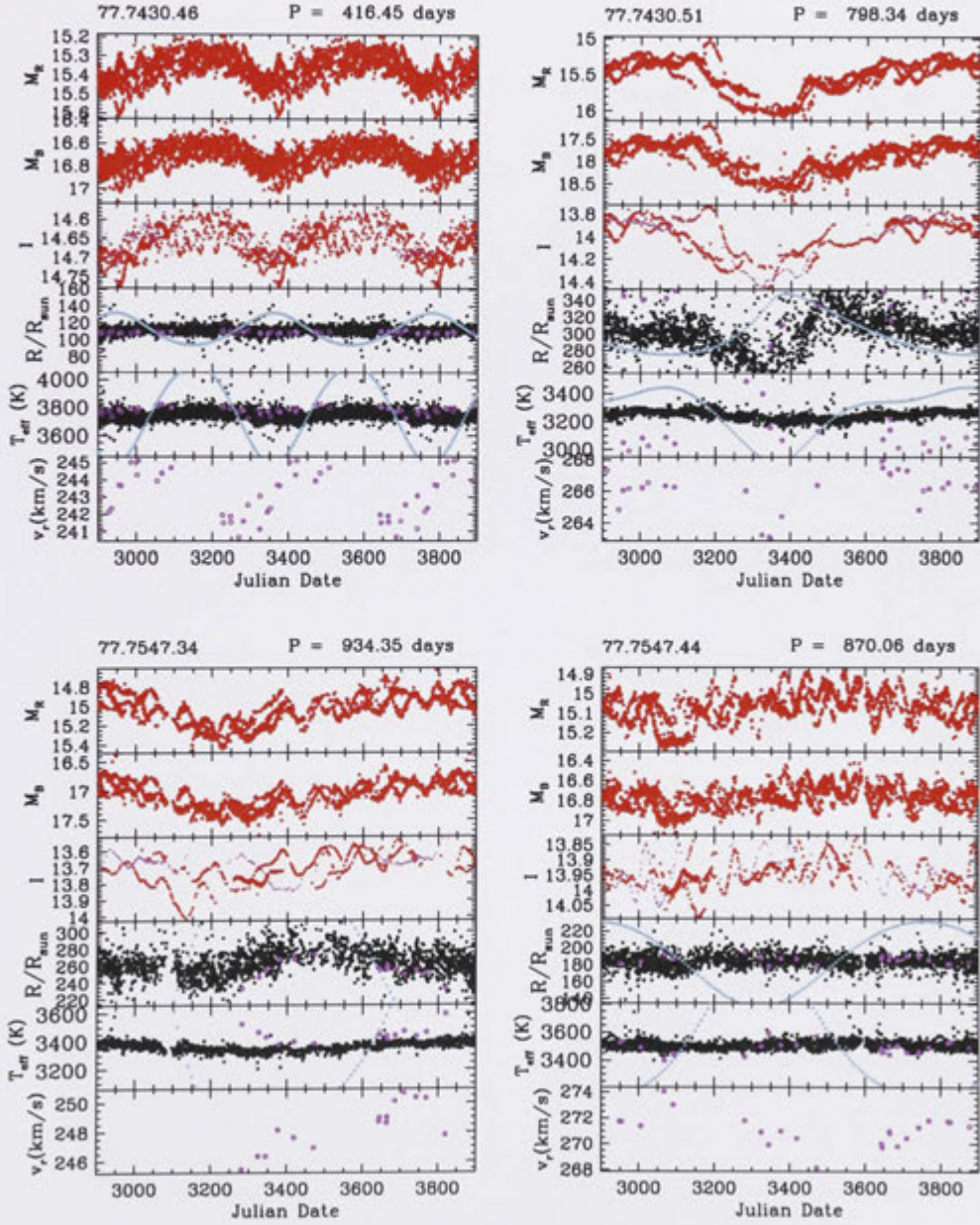


Figure D.2: Same as Figure D.1.



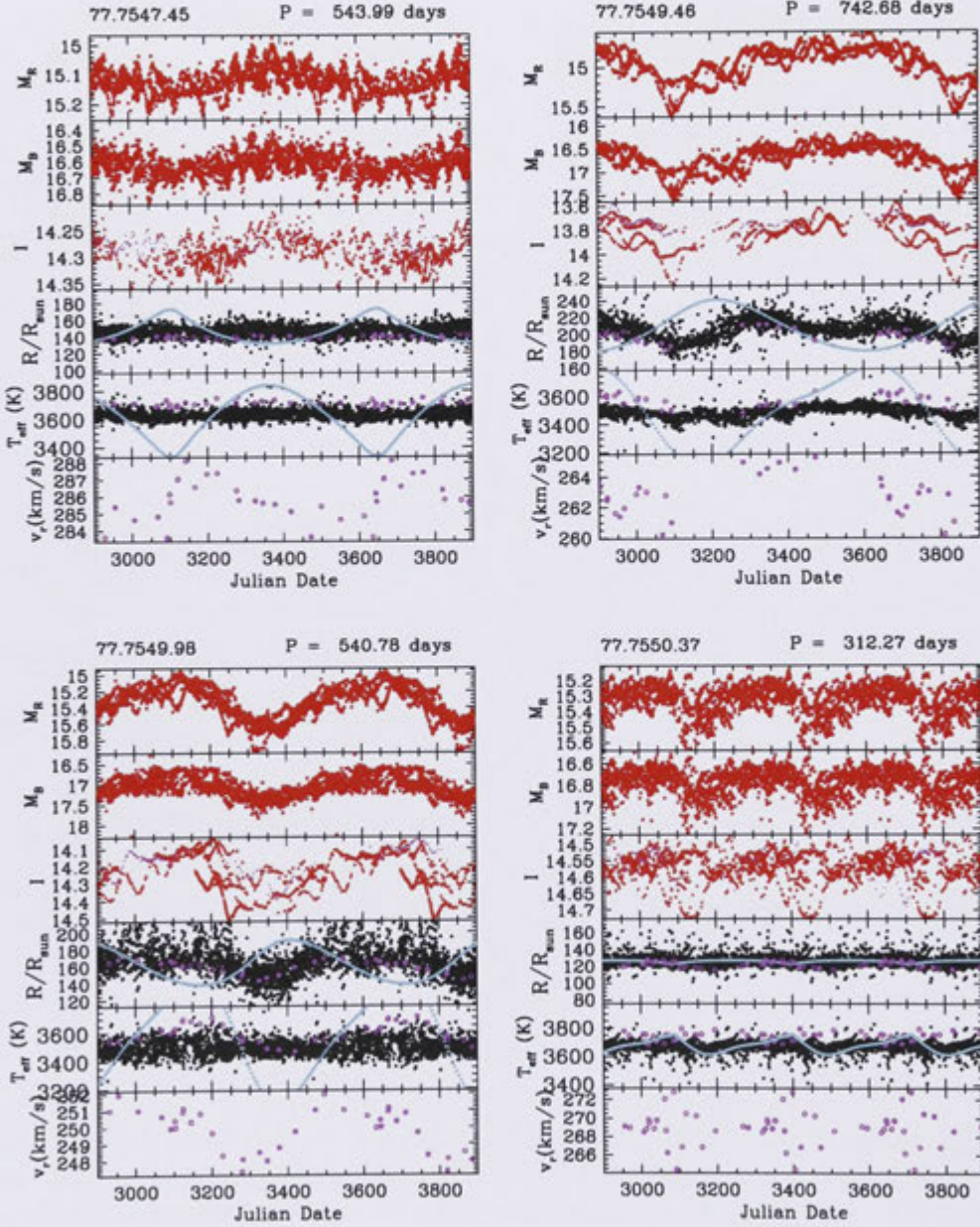


Figure D.3: Same as Figure D.1.

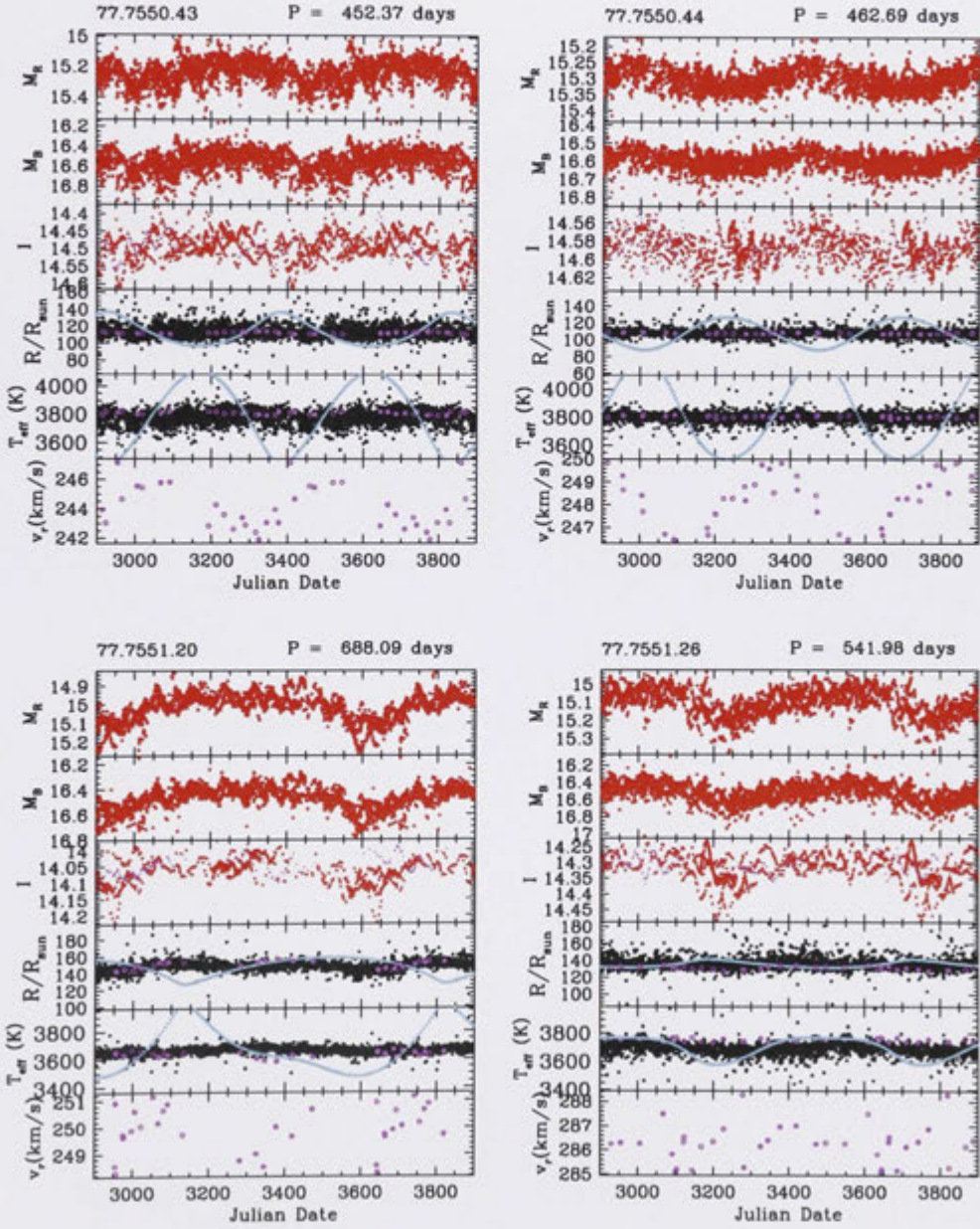


Figure D.4: Same as Figure D.1.



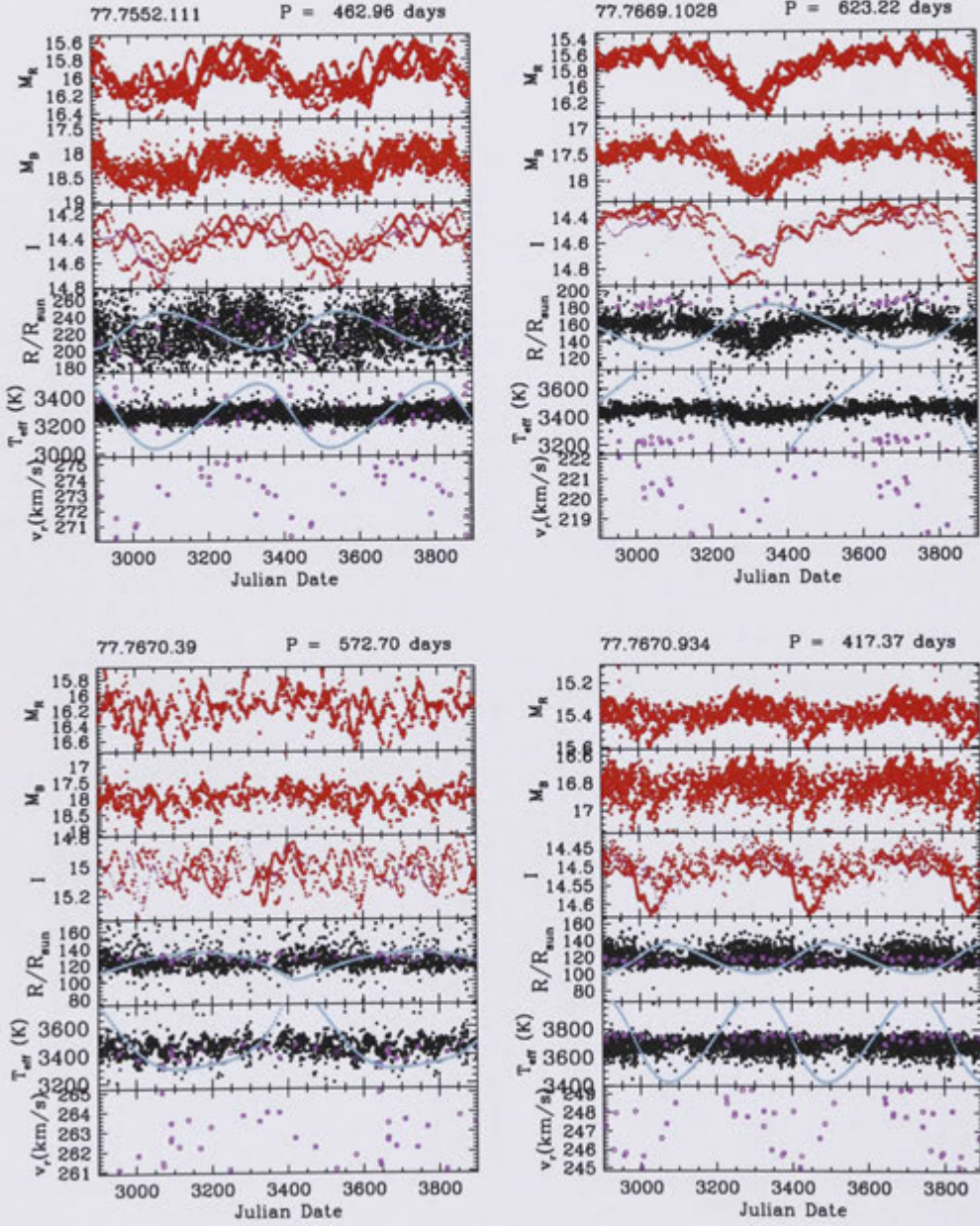


Figure D.5: Same as Figure D.1.

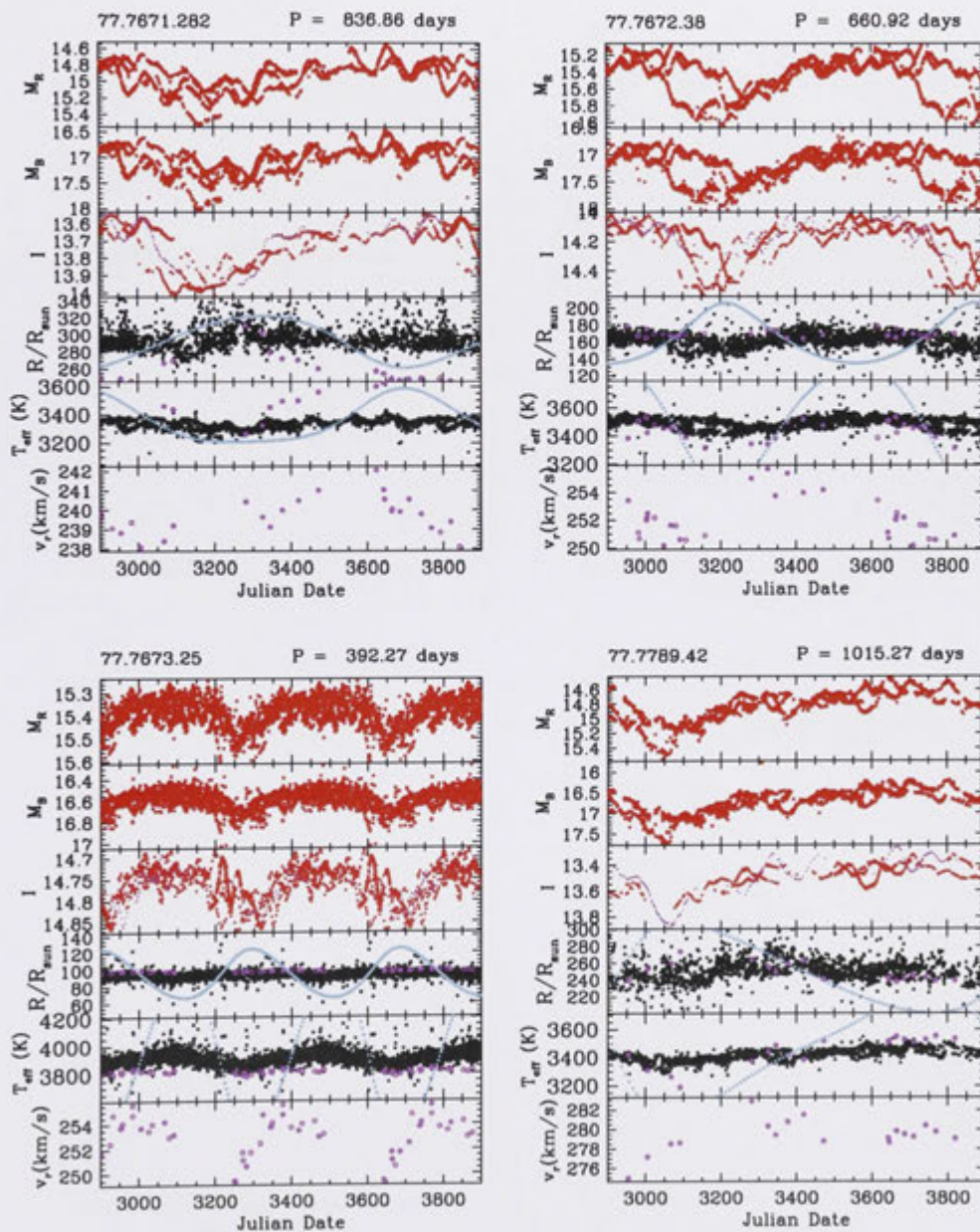


Figure D.6: Same as Figure D.1.



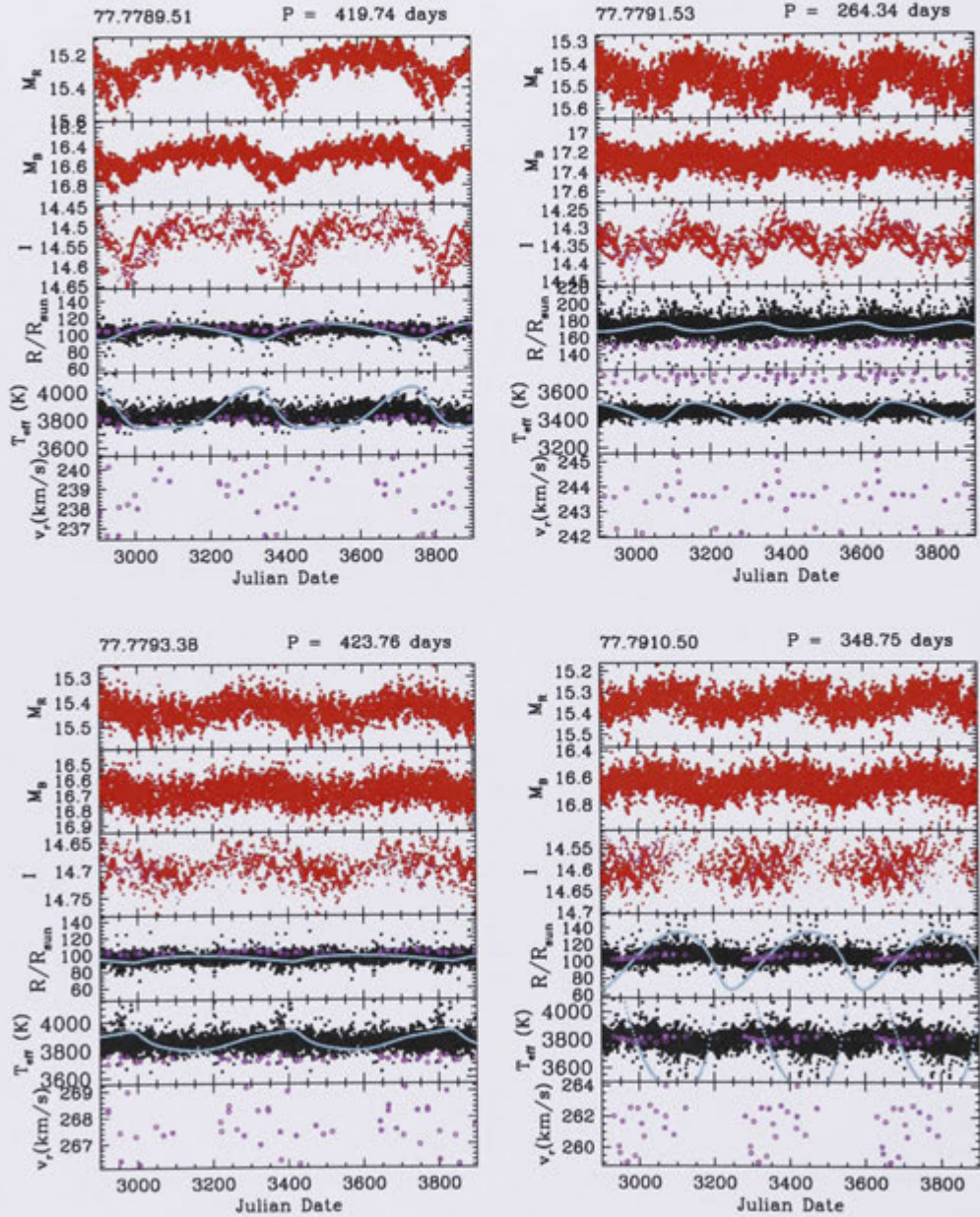


Figure D.7: Same as Figure D.1.



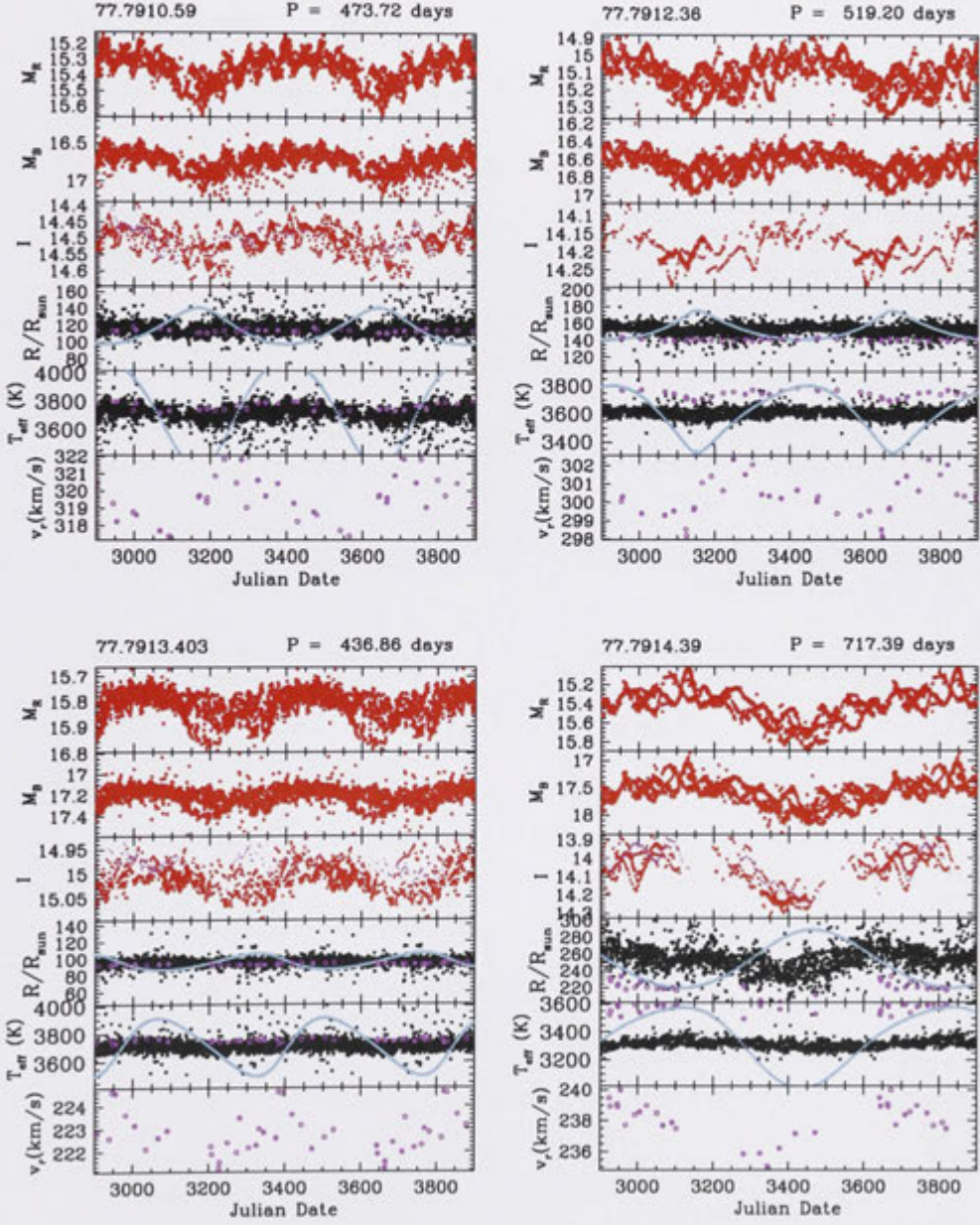


Figure D.8: Same as Figure D.1.

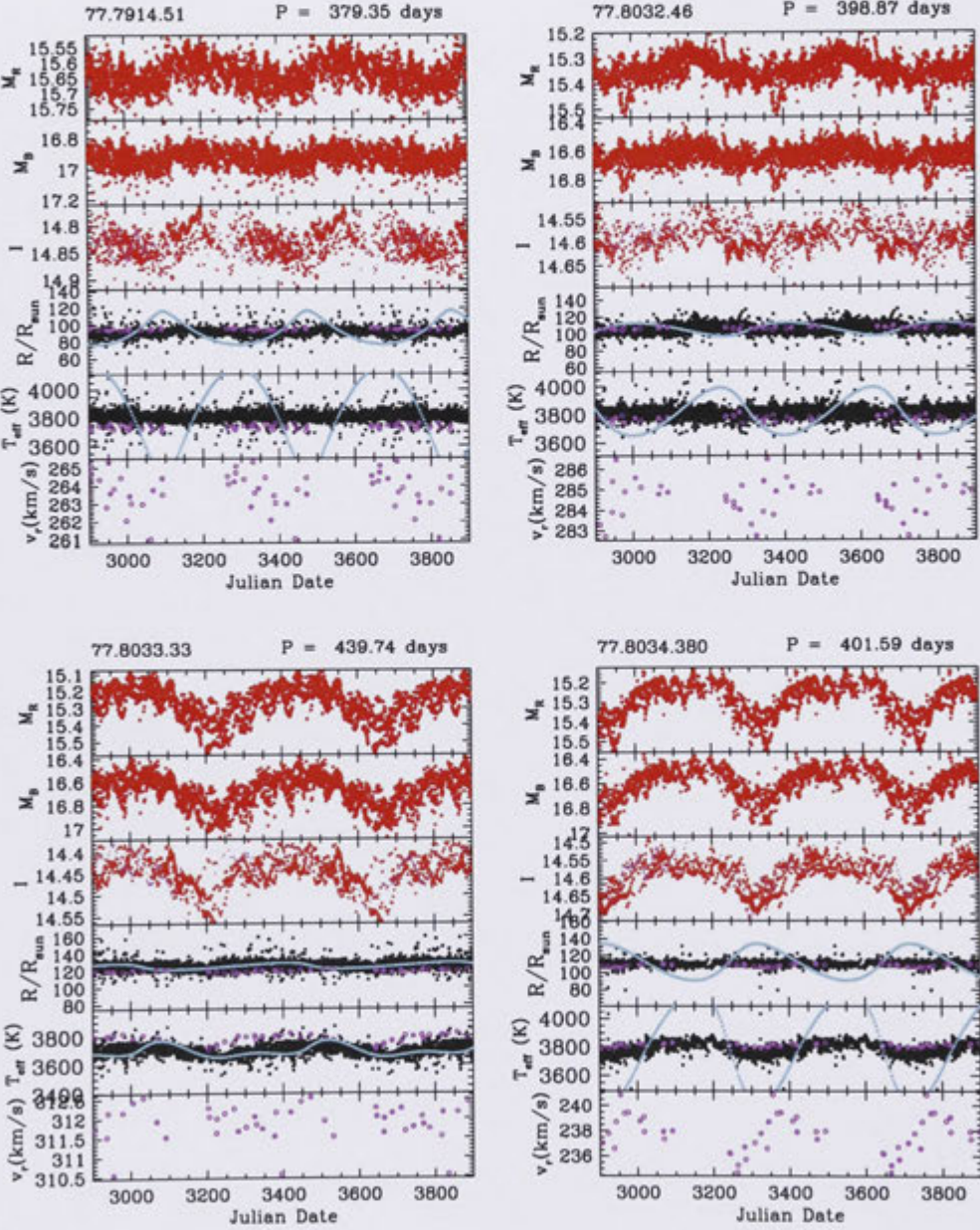


Figure D.9: Same as Figure D.1.

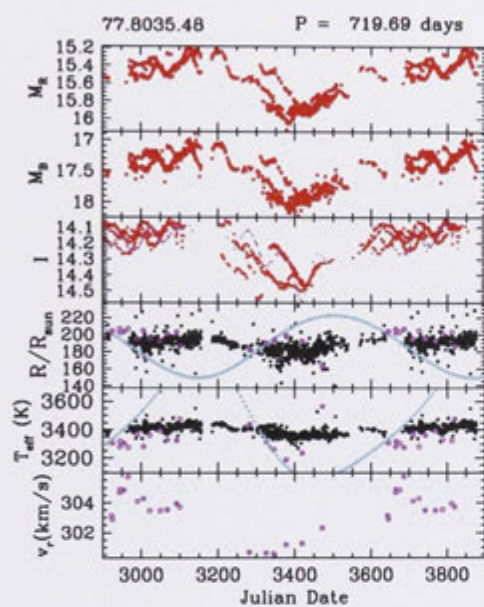


Figure D.10: Same as Figure D.1.





## Sequence E Radial Velocities



**Table E.1:** Radial Velocities of Sequence E Stars. Stars are identified by their MACHO numbers.

| HJD       | 77.7429.189 | 77.7548.68 | 77.7672.98 | 77.7673.79 | 77.7789.152 | 77.7790.72 | 77.7791.115 | 77.7910.41 |
|-----------|-------------|------------|------------|------------|-------------|------------|-------------|------------|
| 2954.8508 | -           | 247.1836   | 270.6885   | 265.7394   | 264.8166    | 264.1844   | 356.8785    | 223.2234   |
| 3005.8604 | -           | 242.5239   | 260.0903   | 258.5819   | 244.1860    | 283.2686   | 331.3213    | 226.0166   |
| 3067.6028 | -           | 237.8895   | 225.7872   | 239.5893   | 261.6783    | 287.9880   | 371.4359    | 258.7258   |
| 3091.5571 | -           | 238.4238   | 251.1337   | 265.9271   | 264.8372    | 286.9947   | 357.3706    | 253.2406   |
| 3280.8611 | 272.6101    | 255.7782   | 284.0382   | 244.0299   | 263.2472    | 257.8580   | 330.5905    | 251.8091   |
| 3324.7628 | 272.0463    | 254.7833   | 248.7445   | 238.5394   | 241.6445    | 276.6594   | 365.3466    | 227.1988   |
| 3344.7984 | 302.7444    | 253.7506   | 225.3991   | 257.7310   | 238.5994    | 282.1365   | 372.2146    | 218.0657   |
| 3376.5812 | 295.7283    | 252.7720   | 224.5430   | 278.4379   | 261.5258    | 291.0966   | 353.8562    | 223.5168   |
| 3418.6897 | -           | 246.9255   | 273.1978   | 240.5749   | 267.5428    | 288.0772   | 330.7243    | 244.1709   |
| 3471.5142 | 303.0329    | 239.1471   | 254.4088   | 254.8756   | 244.7359    | 274.5388   | 368.5684    | 255.4173   |
| 3623.8802 | -           | -          | -          | -          | -           | -          | 372.9120    | -          |
| 3642.8325 | 258.9770    | 250.1424   | 241.6792   | 273.5545   | 235.1525    | 263.4145   | 362.9371    | 262.6712   |
| 3644.8250 | 258.4105    | 249.5308   | 235.0394   | 272.9405   | 244.7821    | 265.5790   | 358.7911    | 260.0475   |
| 3663.8573 | 284.0890    | 252.1868   | 223.0708   | 256.5612   | 246.9317    | 272.1664   | 345.3893    | 255.6085   |
| 3664.8628 | 286.2583    | 251.7897   | 220.0198   | 254.8093   | 244.0158    | 273.3994   | 343.0513    | 257.7978   |
| 3685.6662 | 308.1716    | 253.2069   | 221.2945   | 233.6169   | 253.0680    | 280.7574   | 328.8674    | 242.0641   |
| 3709.7882 | 293.3139    | 253.5271   | 246.5306   | 229.0378   | 268.4498    | 288.4092   | 335.0521    | 226.0995   |
| 3741.6017 | 256.1898    | 254.0319   | 277.9376   | 262.7681   | 267.7674    | 290.1118   | 366.7603    | 219.5844   |
| 3768.6218 | 273.2713    | 254.5472   | 283.0213   | 275.6599   | 250.7668    | 289.7850   | 371.1483    | 227.4145   |
| 3819.5023 | -           | 250.5555   | 222.8380   | 231.9888   | 256.7875    | 278.0466   | 331.9900    | -          |

**Table E.2:** Radial Velocities of Sequence E Stars. Stars are identified by their MACHO numbers.

| HJD       | 77.7910.77 | 77.7912.111 | 77.7914.74 |
|-----------|------------|-------------|------------|
| 2954.8508 | 250.6682   | 223.7452    | 294.0465   |
| 3005.8604 | 298.1713   | 242.9383    | 311.9610   |
| 3067.6028 | 295.5014   | 217.1285    | 320.0665   |
| 3091.5571 | 241.3028   | 230.8909    | 316.7214   |
| 3280.8611 | 297.9548   | 234.7283    | 309.8248   |
| 3324.7628 | 299.7784   | 216.7359    | 320.5855   |
| 3344.7984 | 267.6435   | 229.7542    | 321.7772   |
| 3376.5812 | 235.1142   | 250.0199    | 318.4082   |
| 3418.6897 | 229.6814   | 232.3842    | 302.2198   |
| 3471.5142 | 274.1148   | 227.5479    | 289.4879   |
| 3623.8802 | -          | -           | -          |
| 3642.8325 | 251.2138   | 244.6794    | 320.4452   |
| 3644.8250 | 261.0447   | 243.3174    | 319.5393   |
| 3663.8573 | 295.2852   | 235.6928    | 314.2204   |
| 3664.8628 | 286.7151   | 234.7577    | 314.4216   |
| 3685.6662 | 216.2078   | 221.4717    | 307.4187   |
| 3709.7882 | 261.8198   | 216.0539    | 299.3397   |
| 3741.6017 | 254.1056   | 234.5694    | 291.0329   |
| 3768.6218 | 236.2655   | 243.5422    | 288.6198   |
| 3819.5023 | -          | 217.2858    | 299.6719   |