EVIDENCE FOR MASS EJECTION ASSOCIATED WITH LONG SECONDARY PERIODS IN RED GIANTS

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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 µm 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 µm 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.

Key words: binaries: general – circumstellar matter – stars: AGB and post-AGB – stars: low-mass, brown dwarfs – stars: mass loss – stars: variables: other

Online-only material: color figures

1. INTRODUCTION

When red giants become more luminous than $L \sim 1000 L_\odot$, they begin to vary with periods of variation that fall on six physically distinct period–luminosity sequences1 (Wood et al. 1999; Ita et al. 2004; Soszyński et al. 2007; Fraser et al. 2008). In addition to 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 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); hence, 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; Kiss et al. 2006).

Since the period of the LSP is approximately 4 times longer than that of the fundamental radial normal mode, the LSP cannot be due to normal mode radial pulsation. The most favored explanations for the origin of LSPs are binarity and nonradial g-modes (Wood et al. 1999, 2004; Hinkle et al. 2002, 2009; Derekas et al. 2006; Soszyński 2007), but these and other explanations for the LSPs all have significant problems.

1 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 (Kiss & Bedding 2003; Ita et al. 2004; Soszyński et al. 2007). Some authors designate the corresponding FGB and AGB sequences as distinct sequences.
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 1–4.2 The sequence-D stars exhibit light variations at both a primary period, which is usually on sequence-2 or sequence-3, and an LSP, which falls on sequence-D. Examples of the light curves of typical sequence-D stars are shown in the top three panels of Figure 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 stars that 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 1. These are stars with large amplitude, Mira-like pulsation, high mass loss rates, and thick circumstellar dust shells, and they belong to 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 (SRVs) without obvious LSPs that are typical of sequences 2 and 3 and several R Coronae Borealis (RCB) 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.

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2 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).
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 period 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.

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 sequences, 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 sequences than the remaining stars in the complete samples. The amplitude distribution of the two samples is shown later in Section 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. TESTING FOR CIRCUMSTELLAR DUST USING MID-IR FLUXES FROM THE SAGE SURVEY

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

3.1. The \( K-8 \) Color

In Figure 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, and 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 & Haging 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 2: the separation is seen most easily for the gray 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 \( K-8, J-K \approx (1.1, 1.8) \) 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 mag. 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 (Ivezić 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 that 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 \( T = 2700 K \) 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 \( 7 \times 10^{-6} M_\odot \) yr\(^{-1} \) for a star with \( L = 5000 L_\odot \). These are simple approximations that do not allow for variation of 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 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 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 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 \(K-[8]\) are likely to indicate a star with a dusty disk. This picture is consistent with the \(J-K\) colors of the 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 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 the C-rich SRVs lie mostly in the domain of the C stars with very little mid-IR excess and low mass loss rates. Similarly, the fraction of LSPVs with a \(K\) color rather than the \(K-[8]\) color for the P5 samples. The dashed line marks show the 24 \(\mu\)m magnitude limit \((24 \mu m = 10)\) 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 \(\mu m\) as a function of \(K\) magnitude. The histograms of LSPVs and SRVs in the top panel include both C and O-rich stars.

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 \(\mu m\) measurements from the SAGE survey, as we will now show.

### 3.2. The \(K-[24]\) Color

Figure 3 shows a plot similar to Figure 2 but using the \(K-[24]\) color rather than the \(K-[8]\) color for the P5 samples. The dashed line marks show the 24 \(\mu m\) magnitude limit \((24 \mu m = 10)\) 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 \(\mu m\) as a function of \(K\) magnitude. The histograms of LSPVs and SRVs in the top panel include both C and O-rich stars.

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Figure 3 shows a plot similar to Figure 2 but using the \(K-[24]\) color. It is immediately obvious from comparing Figures 2 and 3 that only a small fraction of the sample was detected at 24 \(\mu m\). 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 \(\mu m\) whereas essentially all stars were detected at 8 \(\mu m\). For the sequence-1 variables, 52% (2077 stars) brighter than \(K = 12\) were detected at 24 \(\mu m\) whereas essentially all stars were detected at 8 \(\mu m\).
Figure 4. Same as Figure 3 but for stars detected at 24 \( \mu \)m in the larger, complete samples.

(A color version of this figure is available in the online journal.)

Given the stronger mid-IR excess exhibited by the LSPVs, one would expect a larger fraction of LSPVs to be detected at 24 \( \mu \)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, 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 fall in distinct groups separated by the line \( J - K = 1.4 \), with the C stars lying above this line. As in Figure 2, the \( J - K \) colors of the C-rich LSPVs in Figure 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 that 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 of behavior is because the winds in Miras are not all spherically symmetric or if it is because the models are too simplistic. 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 also that 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 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 \( \mu \)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 three stars in the combined complete samples with a 24 \( \mu \)m detection but not an 8 \( \mu \)m detection, so that it is possible to compare the \( K - [24] \) excess with the \( K - [8] \) excess essentially for all stars. This is done in Figure 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 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 2–4).

3.3. The Effect of Amplitude on \( K - [24] \) Color

It has been shown above that the existence of an LSP in a red giant seems to induce extra circumstellar dust formation. In this

\footnote{The O-rich models of Groenewegen (2006) follow the same general behavior as the DUSTY models shown here but they tend to be 0.5–1 mag redder in \( K - [24] \) for the higher mass loss rates.}
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 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 in the $K$–$[24]$ color with the 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 mag. 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 6 indicates that the LSPVs that are in the P5 sample have larger average amplitudes than those in the complete sample. This confirms our assertion in Section 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.

4. SUMMARY AND CONCLUSIONS

We have shown that luminous red giant stars that exhibit LSPs 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 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 nonradial 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 Höfner 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 G 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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Figure 6. $K$–$[24]$ 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 $24 \mu$m flux in the P5 sample (red line) and the complete sample (black dotted line).

(A color version of this figure is available in the online journal.)
