Pulsation Time Scales and Amplitudes in a Sample of Bright Semi-Regular Variable Stars

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ABSTRACT. We have analyzed the differential V-band photometric variations of records up to 8 years long in ten M III semi-regular variable stars. Periodograms constructed from each star’s entire record and seasonal intervals were used to find repetitive occurrences of pulsation periods in the range of 10 to 250 days. For every star at least one locus of periods was observed, with many stars showing two distinct distributions of pulsation time scales. The observed pulsation periods and differential V-magnitude semi-amplitudes appear to be correlated such that longer periods correspond to larger semi-amplitudes.

1. INTRODUCTION

Semi-regular (SR) variable stars are typically late-type giant or supergiant stars, showing variability due to pulsation of up to a few tenths of a magnitude. The term “semi-regular” describes a star which lacks a clearly observable pulsation period as seen for Cepheids or even Miras, but whose variations are not as complicated as the truly irregular variables such as V Aql, or υ Cas. The first stars of this class to be discovered were μ Cep by Sir William Herschel in 1782, and α¹ Her, in 1796. The SR stars usually show variability with periods between 30–300 days superposed with longer variation on the order of 1000 days. Additional background information is given by Percy (1985), and Querci (1986).

SR stars have not enjoyed the popularity of other pulsating stars such as Miras or Cepheids because of the difficulty in measuring a dominant pulsation period which can subsequently be included within theoretical models. In order to determine accurately time scales of pulsation, a very long baseline is required. Fortunately, aggressive monitoring of SR stars has recently begun by groups of amateur and professional astronomers such as the AAVSO Photometric Electrography Survey and at the University of Toronto (Percy and Fleming 1992; Percy et al. 1994). Likewise, we have selected a sample group of M III SR stars for long-term examination using the 0.25-m Automatic Photometric Telescope (APT) at the F.L. Whipple Observatory at Mt. Hopkins, Arizona. These stars are part of a project begun in 1986 to monitor bright (3 ≤ V ≤ 8 mag) variable stars (Baliunas et al. 1987). The list of stars appears in Table 1.

We analyzed the time series obtained thus far to search for pulsation time scales in the 10–250 day range.

2. OBSERVATIONS

Automated observing of semi-regular variables with the 0.25-m APT allows very low cost, long-term data acquisition from a prime photometric site. The observing sequence and precision of the photometric data from this telescope are de
which averaged approximately 0.01 mag in the V filter. All precision of the resulting observations is given by the seasonal scatter of the check-minus-comparison differentials, which averaged approximately 0.01 mag in the V filter. All observations were corrected for differential extinction with seasonal mean extinction coefficients determined on occasional nights of standard star observations and reduced to the Johnson system with long-term mean transformation coefficients. Night-to-night and seasonal temperature variations are a major source of the resulting 0.01 mag scatter. This study will concentrate on the V (550±45 nm) measurements only. The photometric differential V magnitudes are shown in Figs. 1 and 2. Each star’s record is split up to nine 200–250-day observing seasons.

Although changes in the light curves for SR stars are evident from cycle to cycle, in several cases a dominant period is clearly marked over an extended period of time. Percy et al. (1989) measured a persistent 63-day period for the M6 III star EU Del. However, Percy et al. (1993) describe the light curve of R Lyr as “sporadic” in comparison, but containing episodes during which a pulsation period might be measured. Likewise, Szatmáry and Vinkó (1992) note transitory periods in the long-term variability of the M5 Ib–II star Y Lyn.

While no simple mechanism for pulsation exists, it may be possible to find some degree of regularity in their light curves which can suggest a likely time scale of pulsation. Thus, the semi-regular behavior can possibly be explained by a very complex variation brought about by the combination of two or more oscillations, each of which may possibly be more or less regular and varying independently of the others. In addition, the strength of these oscillations may grow and decay with time, with the result that different modes are more prominent at any given epoch. Therefore, the most clearly recognizable time scale of pulsation may change with time. Cadmus et al. (1991) noted the change in amplitude and period for three SR stars, and suggest mode switching between the fundamental pulsation mode to an overtone pulsation as the mechanism producing the complex light curve.

Measurements made over longer intervals may have

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**Table 1**

Characteristics of the M-type SRs

<table>
<thead>
<tr>
<th>Name</th>
<th>HD Number</th>
<th>Spectral Type</th>
<th>V</th>
<th>B - V</th>
<th>Comparison Star</th>
<th>Check Star</th>
</tr>
</thead>
<tbody>
<tr>
<td>RX Lep</td>
<td>33664</td>
<td>M6 III</td>
<td>5.68</td>
<td>1.46</td>
<td>33093</td>
<td>33802</td>
</tr>
<tr>
<td>η Gem</td>
<td>42995</td>
<td>M3 III</td>
<td>3.28</td>
<td>1.61</td>
<td>41116</td>
<td>44478</td>
</tr>
<tr>
<td>BC CMI</td>
<td>64052</td>
<td>M4 III</td>
<td>6.31</td>
<td>1.59</td>
<td>63799</td>
<td>65345</td>
</tr>
<tr>
<td>UX Lyn</td>
<td>77443</td>
<td>M4 III</td>
<td>6.60</td>
<td>1.51</td>
<td>76944</td>
<td>77912</td>
</tr>
<tr>
<td>RS Cnc</td>
<td>78712</td>
<td>M6 III</td>
<td>5.95</td>
<td>1.67</td>
<td>78235</td>
<td>76572</td>
</tr>
<tr>
<td>ST UMa</td>
<td>98592</td>
<td>M4 III</td>
<td>6.28</td>
<td>1.68</td>
<td>99606</td>
<td>101133</td>
</tr>
<tr>
<td>TU CVn</td>
<td>112964</td>
<td>M5 III</td>
<td>5.88</td>
<td>1.59</td>
<td>112850</td>
<td>112984</td>
</tr>
<tr>
<td>FS Com</td>
<td>113866</td>
<td>M5 III</td>
<td>5.60</td>
<td>1.59</td>
<td>113866</td>
<td>113848</td>
</tr>
<tr>
<td>30 Her</td>
<td>148783</td>
<td>M6 III</td>
<td>5.01</td>
<td>1.52</td>
<td>150099</td>
<td>149630</td>
</tr>
<tr>
<td>R Lyr</td>
<td>178565</td>
<td>M5 III</td>
<td>4.04</td>
<td>1.59</td>
<td>178621</td>
<td>177196</td>
</tr>
</tbody>
</table>

*Most of the information was obtained from the SIMBAD database, operated by the Centre de Données Astronomique de Strasbourg (CDS).
greater success at characterizing the interaction of competing pulsation periods. For example, Loeser et al. (1986) measured two persistent periods for the SR star V CVn (M6 III) using 60 years of AAVSO naked-eye observations. On the other hand, long-term observations of W Cyg by Percy et al. (1993) suggest the star is beating with close but variable periods near 130 days. The intermediate-term time series currently available for this sample of stars indicate persistent regularities that may eventually lead to some illumination of the underlying physical processes involved in producing the complex variability.

3. PULSATION PERIODS AND AMPLITUDES

Periodogram analysis was used to measure pulsation time scales for each star observed. We have concentrated our search for variations to time scales less than the length of the observing season (typically 200–250 days) and have analyzed each observing season individually. The repeated occurrence of a particular pulsation period (or set of periods) from season to season will be a good indication of the primary pulsation periods for a particular star. Because the variations are semi-regular, different periods may be prominent in any given observing season. Therefore, each observing season was analyzed individually to minimize the above effects and to provide better statistics on the recurrence of possible pulsation periods. This technique works best for phenomena which occur on time scales that are shorter than the observing season, i.e., ≤ 150 days. For pulsations with longer periods, it may not be possible to determine the period accurately from a single season of data, and therefore a longer baseline must be used (see below).

A periodogram (Scargle 1982; Horne and Baliunas 1986) was calculated for each interval, e.g., one season and significant peaks were recorded. In a few cases, as many as three peaks were observed simultaneously within the same observing season. To test the validity of the multiple peaks, each was filtered from the periodogram sequentially (Baliunas et al. 1985) and the resultant periodogram examined for the previously recorded secondary peak. Peaks which remain after filtering are not artifacts due to spectral leakage but may still be influenced by the observing window.

3.1 Recurring Periods from Individual Seasons

For every star in the sample (except for RS Cnc), recurring periods were found in several seasons that lie close to one another. The semi-regular and possibly competing variations could describe the scatter in observed pulsation periods which, although not exact from season to season, may suggest an overall time scale of pulsation. An examination of the distributions of periods from each observing season revealed clustering at one or two loci repeating from season to season. We interpret the recurrence of these periods to suggest that they are important contributors to the overall variation.

Some periods occurred only once within one season of the available time series. If these periods are due to pulsation, it is possible that they are more visible at other times but not during our limited record, but might recur in longer time series. Many authors (Percy and Fleming 1992; Glasby 1969) note the presence of very long (>250 day) modulations in the light curves of SR stars. While such long-term modulation is immediately apparent in the record of stars such as RX Leporis, investigation and quantitative analysis of such long-term variations is difficult given as the available time series.

The periods were averaged in each locus for all the seasons to form \( \langle P \rangle \) and the standard deviation of the distribution, \( \text{rms}(P) \). Table 2 contains mean periods and semi-amplitudes, and their standard deviations, obtained from a season-by-season analysis, and the number of periods, \( N \), within each locus used to derive the average period and semi-amplitude. The recognition of these loci was done arbitrarily; a statistically significant distribution of seasonal pulsation periods will require many years of data. However, the recurrence of some periods in almost every observing season suggests that we are successfully measuring significant contributors to the semi-regular variation, within the period range searched.

Three stars in Table 1 (\( \eta \) Gem, RS Cnc, and ST UMa) have periods that are close to the length of an observing season. Because of this, it is difficult to accurately measure the pulsation period because <2 cycles are present within the observing season. Therefore, for these stars we have repeated the analysis using two consecutive seasons of data. This extends the baseline from 200–250 days to 550–600 days and thus permits a more accurate measurement of these longer periods. The addition of another observing season does introduce complications in the power spectrum due to the intra-seasonal gap which is now in the middle of the record. However, it is straightforward to identify and accu-
Table 4

<table>
<thead>
<tr>
<th>Star</th>
<th>Period (days)</th>
<th>Semi-amplitude (mag)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RX Lep</td>
<td>98</td>
<td>0.133</td>
</tr>
<tr>
<td>η Gem</td>
<td>238</td>
<td>0.083</td>
</tr>
<tr>
<td>BC CMi</td>
<td>27</td>
<td>0.026</td>
</tr>
<tr>
<td>UX Lyn</td>
<td>37</td>
<td>0.052</td>
</tr>
<tr>
<td>RS Cnc</td>
<td>242</td>
<td>0.253</td>
</tr>
<tr>
<td>ST UMa</td>
<td>132</td>
<td>0.122</td>
</tr>
<tr>
<td>TU CVn</td>
<td>44</td>
<td>0.056</td>
</tr>
<tr>
<td>FS Com</td>
<td>55</td>
<td>0.063</td>
</tr>
<tr>
<td>30 Her</td>
<td>60</td>
<td>0.129</td>
</tr>
<tr>
<td>R Lyr</td>
<td>65</td>
<td>0.058</td>
</tr>
</tbody>
</table>

3.2 Overall Persistence of Periods Inferred from the 8-Year Records

In addition to searching for periods from each season of data, we have also analyzed the entire record for each star to check for periods which might persist over an extended length of time. In Table 4, the most significant period and its semi-amplitude are given for each of the ten stars in our sample. Each of the pulsation periods in Table 4 are close to one of the periods listed in Tables 2 and 3, and all are within ±2 s.d. of the \( \langle P \rangle \) in Tables 2 and 3.

While using the entire time series for a star reveals those periods which persist for several years, analyzing the data season by season permits the detection of transitory influences to the light curve and the range of pulsation period one would expect from a shorter time series. For example, Percy et al. (1993) report a 56-day period for FS Comae, which agrees with our 55-day period. On the other hand, Percy et al. (1993) find a 53-day period for R Lyrae which falls between the 65-day and 25-day loci of periods determined season by season in Table 2. The locus of 25 days is based on only two detections, and the 65-day period is also present in the periodogram of the entire time series. Percy et al. (1994) find an approximate pulsation time scale of 35 days for BC CMi which is between the 24-day and 43-day mean periods we have observed, and a period between 80–90 days for 30 Her (g Her), which is longer than the periods in Table 2 of at 64 and 41 days. Thus, in analyzing the time series of SR variables, the interval of analysis matters.

4. DISCUSSION

In Fig. 3 we plot the mean pulsation semi-amplitudes versus the mean periods for each locus described above. For the stars with longer periods, the values in Table 3 were used instead of those in Table 2. A least-squares fit to the data has the relationship

\[ a = 0.041 + 7.2 \times 10^{-4} P, \]

with a linear correlation coefficient, \( r = 0.67 \), and a 99.8% probability against a distribution with \( r = 0.67 \) and \( N = 18 \) arising from data with no correlation. This confirms the suggestion of Percy and Fleming (1992) that such a correlation might exist.

Certainly, a longer database of time-series measurements will permit an increased awareness of the primary pulsation periods, and combined with a larger sample of stars, a more systematic search for correlations between pulsation periods and other intrinsics can be made. In addition, our sample does not include SRc (supergiant) stars, nor any stars of spectral types N, R, or C. Therefore it remains to be seen if correlations with spectral type exist for those other SR stars.

5. CONCLUSIONS

Pulsation time scales and semi-amplitudes were recorded for ten semi-regular stars. The results from seasonal records and the records over the entire 8 years of observations leads to the identification of the persistence and variation of periods over longer intervals.

A correlation between period and semi-amplitude was observed. This result echoes similar correlations seen for δ Cephei stars and for Miras (Eggen 1975). However, the range of semi-amplitudes does not match either the Miras or the Cepheids which have semi-amplitudes that are as much as an order of magnitude larger in the period range observed for these SR stars.

The relatively small semi-amplitudes of SR stars and their complicated time series makes them a particularly challenging class of objects to analyze. Therefore, we present these periods as a work "in progress," since a clearer understanding of the true mechanism which creates these complicated variations can only be obtained through continued diligence in both obtaining new data, as well as searching for periods.

Long-term monitoring, such as done by the Smithsonian
0.25-m APT as well as the work done by the AAVSO and elsewhere is essential to provide empirical constraints on the intricate pulsation models needed to describe SR-star behavior.

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