Session IV

VARIABILITY

https://doi.org/10.1017/S0074180900002369 Published online by Cambridge University Press

Janet Mattei, a Turkish student, Zeki Aslan, and Tom Lloyd Evans at the construction site of the Kazan University 1.5–m telescope on Bakırlıtepe. The telescope is now in operation; the observatory itself was officially dedicated on Sept. 5, 1997.

https://doi.org/10.1017/S0074180900002369 Published online by Cambridge University Press

TREND ANALYSIS OF 51 CARBON LONG-PERIOD VARIABLES

JANET AKYÜZ MATTEI AND GRANT FOSTER
American Association of Variable Star Observers
Cambridge, MA 02138, U.S.A.

Abstract. We have performed a trend analysis of 51 long-period variables (LPVs) of spectral types C, R, N, and S using 90 years of AAVSO data. We studied the periods and amplitudes, as well as the fall time (the time from maximum light to minimum), the rise time (from minimum to maximum), and the magnitudes at maximum and minimum. We also looked for time evolution of period and amplitude in the light curves themselves. The periods are more stable than the other parameters, with longer-period stars more likely to show period fluctuations than shorter-period stars. Fall time and rise time tend to evolve oppositely (mirror evolution), keeping the period fairly constant, whereas magnitude at maximum and minimum often evolve together (parallel evolution). About half of these stars are getting fainter, especially at maximum light, showing a secular dimming of magnitude at maximum; *none* shows a secular brightening.

1. Introduction

The purpose of the American Association of Variable Star Observers (AAVSO) is to coordinate variable star observations made largely by amateur astronomers worldwide; to collect, evaluate, process, and archive them, and to publish and disseminate them to researchers around the world. Over 8 million observations have been compiled since the founding of AAVSO in 1911; these make up the *AAVSO International Database*. Data from 1961 to date have been digitized and processed, and are accessible. The earlier data which have been digitized are being processed and will be added into the database within one year, thus creating the longest computer-readable variable star database in the world. Annually, over 300,000 observations are submitted to the AAVSO from observers worldwide for inclusion in

R.F. Wing (ed.), The Carbon Star Phenomenon, 155-163.

the database. These observations are digitized, processed, and subjected to quality control checks to ensure the highest level of reliability.

The AAVSO receives over 300 requests each year from astronomers and educators for data and services to help schedule observing runs using ground-based and satellite telescopes, to provide simultaneous optical coverage of observing targets and immediate notification of their activity during particular satellite observing programs, to correlate multi-wavelength data, and to carry out collaborative research to analyze the long-term behavior of variable stars.

2. Data

The AAVSO Observing Program contains 4,467 stars, of which 1,967 (44%) are *Mira* and *semiregular* type LPVs. Of these, 97 of 1361 Mira variables (7%) and 96 of 606 semiregular variables (16%) are carbon stars or S stars (spectral types C, N, R, and S).

The objective of this study is to search for trends in light curve parameters, such as period, amplitude, rise and fall time, etc. of 51 periodic carbon stars for which long-term data, i.e. over 90 years, exist in the AAVSO database. For this study we have utilized two sets of AAVSO data. The first is individual observations defining the light curve from JD 2,437,600 (October 1961) to 2,450,000 (October 1995). For a few of the more interesting stars, we extracted from the archives AAVSO data covering a longer time span, typically beginning about JD 2,420,000 (August 1913); we are preparing papers on detailed study of some of the most interesting individual stars.

For the second set of data we have utilized observed dates and magnitudes of maxima and minima, going back to 1900, that have been determined homogeneously by the AAVSO using Pogson's method. This practice was begun by Leon Campbell in 1926 (Campbell 1926) and continued by successive AAVSO directors (Campbell 1955, Mattei et al. 1975). In this data set the basic data determined are: T_n, time of maximum for cycle n; M_n, magnitude at maximum; t_n, time of minimum; and m_n, magnitude at minimum. These enable us to define the following *derived parameters* for each cycle: $P_n = T_{n+1} - T_n$, period; $F_n = t_n - T_n$, fall time; $R_n = T_{n+1} - t_n$, rise time; and $A_n = M_n - m_n$, amplitude (see Figure 1). For each star we studied the six parameters P_n, F_n, R_n, M_n, m_n, and A_n. The time series for these derived parameters constitute our second basic data set, and yield a very clear picture of the changes of the star's behavior over time.

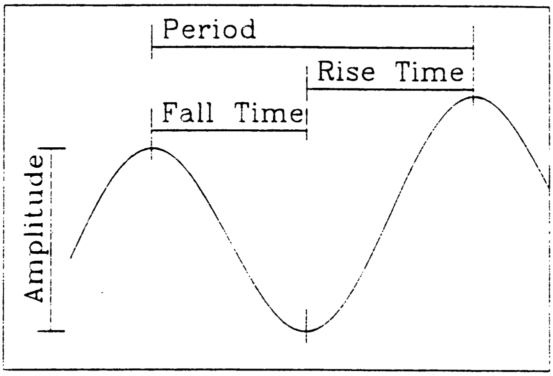

Figure 1. Derived parameters studied herein: Period (time from max to max), fall time (from max to min), rise time (from min to max), and amplitude.

3. Analysis Methods

Because we have two different types of data (derived parameters, and the individual observations themselves), we need two different approaches to search for time evolution of the fluctuations.

We searched for trends in the time series of the derived parameters by fitting low-order orthogonal polynomial functions of cycle number, from 1^{st} degree (linear) to 12^{th} degree. The lower-order polynomials detect very simple trends, while higher-order polynomials detect more complex trend patterns. Each polynomial fit generates a χ^2 test statistic, and all tests were evaluated at the 95% confidence level. A statistically significant fit indicates, first and foremost, that the data are *not* merely random fluctuations about a constant mean value, *i.e.* it establishes the existence of time evolution in the data. Second, the highest polynomial degree which detects significant signal indicates the *complexity* of the trend; a linear fit is the simplest trend shape, but a 12^{th}-order polynomial can model a very complex signal shape. Hence we recorded, for each variable, the highest significant polynomial degree. We emphasize that the lack of any statistically significant fit does *not* establish the absence of a trend; a trend might be present, but with a signal strength too low to detect. We also used the results of the 1^{st}-degree polynomial fits (linear regression) to note the presence of secular trends.

To analyze the light curve for periodicity we applied two techniques. First, we used the CLEANEST Fourier spectrum (Foster 1995). It is designed to compensate for the difficulties associated with uneven time spacing *and* is capable of describing the time evolution of the period and amplitude. For its statistical treatment, we adopted the stricter statistical standards outlined in Foster (1996a, 1996b). Second, we used wavelet analysis. Traditional wavelet analysis is quite good for quantifying period and amplitude changes

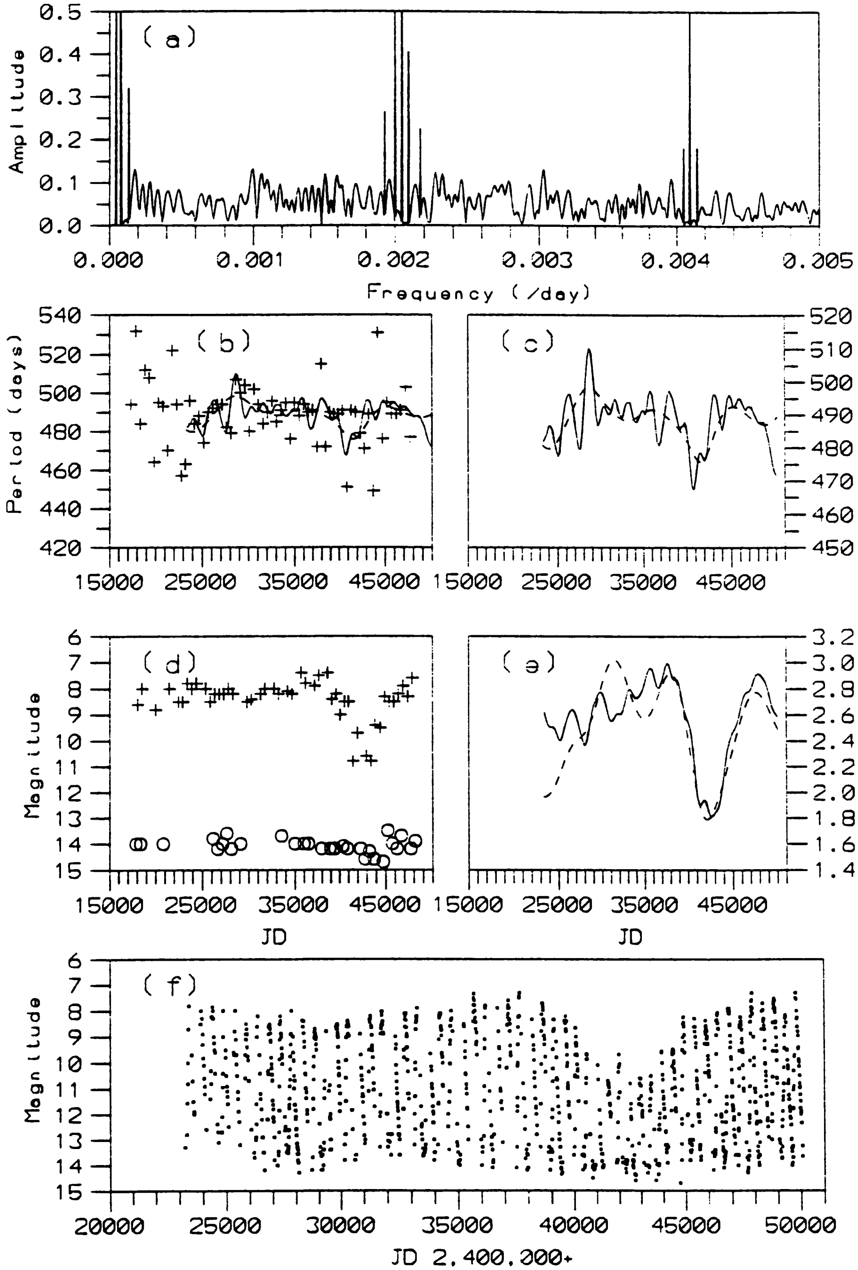

Figure 2. Results for W Aql. (*a*) CLEANEST Fourier amplitude spectrum. (*b*) Period from 90 years of AAVSO maxima and minima data (*plus signs*) compared to period analysis from CLEANEST (*dashed line*) and WWZ (*solid line*). (*c*) Period from CLEANEST (*dashed line*) and WWZ (*solid line*) using individual observations. (*d*) Magnitudes at maxima (*plus signs*) and minima (*circles*) from 90 years of AAVSO maxima and minima data. (*e*) Amplitude from CLEANEST (*dashed line*) and WWZ (*solid line*). (*f*) Light curve of 10-day averages of individual observations.

https://doi.org/10.1017/S0074180900002369 Published online by Cambridge University Press

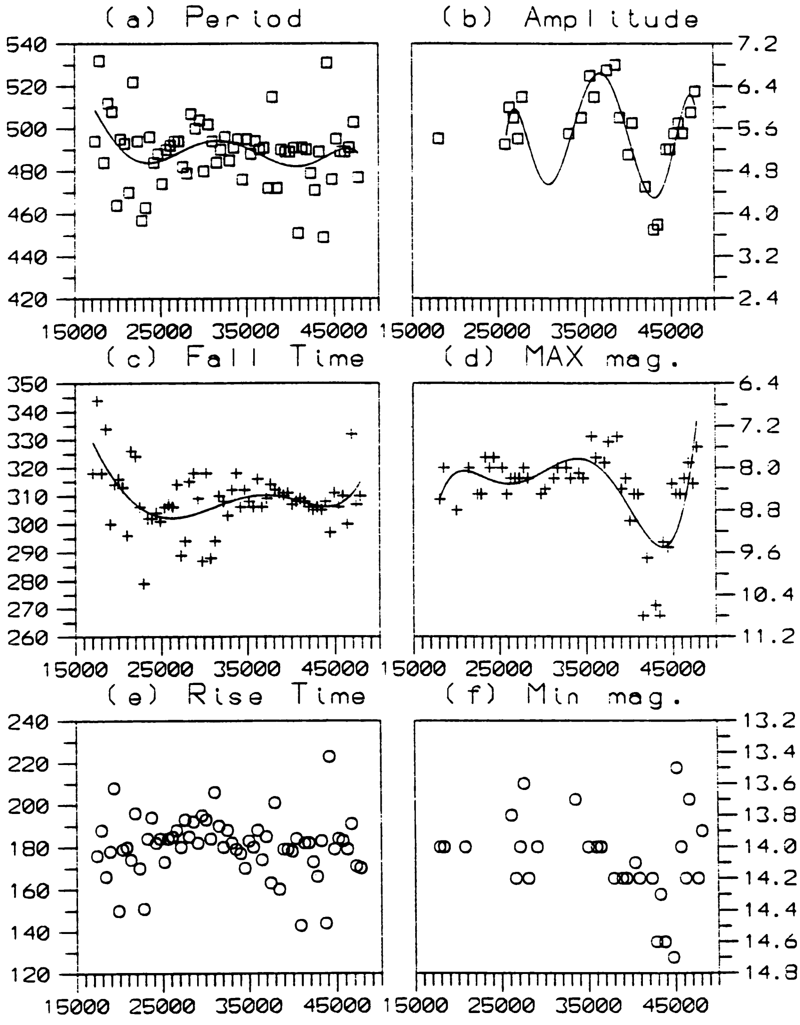

Figure 3. Further results for W Aql using 90 years of AAVSO maxima and minima data. (*a*) Period from max to max. (*b*) Amplitude from max to min. (*c*) Fall time. (*d*) Magnitude at maximum. (*e*) Rise time. (*f*) Magnitude at minimum.

for evenly sampled time series, but notoriously *bad* for unevenly sampled time series. Therefore we adopted the *weighted wavelet Z-transform*, or WWZ (Foster 1996c), which again is specifically designed to compensate for the difficulties of irregularly sampled data. Overall, the results of both methods were in quite good agreement with each other, and with the analysis of the derived parameters, arguing strongly for the robustness of these (relatively new) techniques. A sample of the results for each test is given in Figures 2 and 3 for the interesting S-type star W Aql.

TABLE 1. Trend results for Carbon and S–type LPVs. For the Period, Rise Time, and Fall Time, the units are *days*; for magnitudes at maximum and minimum, and amplitude, the units are *visual magnitudes*.

Star	Period Ave.	PD	Fall Ave.	PD	Rise Ave.	PD	MAX Ave.	PD	min Ave.	PD	Amp Ave.	PD
R And	409.9	–	259.9	3	150.0	5	7.0	6	14.4	3	7.4	–
RR And	328.4	–	157.4	5	171.2	5	9.2	–	15.0	8	6.0	2
ST And	334.7	2	161.4	6	173.3	2	8.9	10	11.1	10	2.2	9
W And	396.1	–	228.7	–	167.4	5	7.6	1	13.8	12	6.2	7
X And	345.7	7	219.1	10	126.6	–	9.1	4	14.7	5	5.7	–
W Aql	489.1	4	308.6	3	180.5	–	8.4	7	14.1	–	5.6	7
X Aqr	312.3	6	181.5	6	130.3	5	8.4	–	14.4	–	5.7	–
V Aur	352.4	3	163.2	6	189.3	11	9.3	11	12.2	3	2.9	11
R Cam	270.0	5	147.8	5	122.3	4	8.4	9	13.4	12	5.0	9
S Cam	327.1	–	158.9	–	168.2	–	8.4	9	10.4	5	1.9	11
T Cam	374.1	4	198.6	7	175.1	5	8.1	4	13.9	7	5.8	7
R Cap	346.3	1	197.1	6	148.9	12	10.8	6	13.7	6	3.1	4
S Cas	612.5	9	349.5	9	262.9	–	9.4	1	15.0	1	5.4	3
U Cas	276.6	–	155.7	12	120.9	5	8.6	11	14.9	3	6.2	3
W Cas	405.2	–	220.6	1	184.5	5	8.9	12	11.9	2	2.9	6
X Cas	425.1	12	189.3	10	235.8	4	10.2	12	12.3	6	2.2	12
RV Cen	445.2	11	197.7	9	247.2	12	7.7	3	10.2	6	2.5	7
S Cep	486.7	9	211.5	3	275.2	5	8.4	11	11.1	10	2.6	8
W Cet	351.6	–	170.1	7	182.3	9	8.0	3	14.4	4	6.4	7
R CMi	337.4	–	177.1	12	160.3	4	8.0	12	10.9	9	3.0	4
T Cnc	374.1	–	273.4	9	175.1	–	8.1	–	13.9	–	5.8	–
V Cnc	271.9	–	147.5	12	124.5	–	7.9	1	12.9	11	5.0	6
V CrB	357.4	–	211.9	2	145.5	10	7.9	11	11.2	10	3.3	10
χ Cyg	408.7	5	239.8	5	168.7	2	5.2	3	13.5	1	8.4	1
R Cyg	427.3	–	272.7	–	154.5	–	7.6	6	13.9	5	6.3	–
RS Cyg	416.9	3	194.3	9	222.6	9	7.3	4	8.8	11	1.5	6
S Cyg	322.7	–	161.3	5	161.3	3	10.3	12	15.8	10	5.5	12
U Cyg	464.5	6	241.9	6	222.6	2	7.5	8	10.8	5	3.4	1
V Cyg	421.0	12	227.1	2	193.8	–	9.3	11	12.9	11	3.6	11
WX Cyg	409.7	10	211.9	3	197.7	6	10.0	11	12.7	11	2.8	10
Z Del	304.4	–	158.9	–	145.5	–	9.0	10	14.6	1	5.5	–
T Dra	420.9	3	233.8	8	187.1	5	9.9	12	12.5	10	2.6	11
R For	388.9	–	186.1	–	202.7	–	9.2	4	12.3	4	3.1	1
R Gem	370.3	–	238.6	–	131.6	3	7.1	–	13.4	6	6.3	3
T Gem	287.7	–	150.5	1	137.1	6	8.7	4	14.2	7	5.5	7
R Lep	433.1	3	197.6	5	236.3	10	7.2	12	9.9	12	2.7	2
S Lup	342.3	–	165.2	5	177.0	6	8.7	6	13.1	5	4.2	5
R Lyn	378.5	–	211.9	3	166.6	3	8.0	4	13.8	1	5.8	7
S Lyr	438.5	4	258.8	8	179.8	4	10.9	5	15.0	–	4.0	4
U Lyr	456.6	3	216.9	4	239.2	8	9.6	4	11.9	12	2.2	5
RR Mon	393.2	9	234.2	10	159.4	10	9.7	1	15.0	–	5.3	3
V Oph	297.9	–	152.7	11	145.2	11	7.7	1	10.3	4	2.6	1
R Ori	379.6	–	219.8	2	159.8	7	9.6	2	13.1	–	3.6	2
RZ Peg	437.3	–	245.8	9	192.1	11	8.7	6	12.7	–	4.0	4
RZ Per	354.9	–	189.2	10	165.7	5	9.5	12	13.7	7	4.2	11
Y Per	251.5	2	126.8	3	124.8	3	8.5	4	10.4	11	1.9	8
ST Sgr	393.9	–	221.3	6	172.0	6	8.7	–	15.8	–	2.2	–
T Sgr	391.8	2	205.9	8	185.9	6	8.1	5	12.5	5	4.3	–
Z Tau	482.2	1	280.1	–	202.9	1	10.5	11	13.8	5	3.3	7
S UMa	226.0	–	121.2	10	104.7	4	7.9	5	11.6	6	3.7	6
RU Vir	436.8	7	225.7	11	210.8	8	9.7	11	13.1	9	3.3	–
SS Vir	356.2	4	167.8	3	188.4	4	6.9	5	9.0	8	2.2	8

https://doi.org/10.1017/S0074180900002369 Published online by Cambridge University Press

4. Overall Results

Table 1 lists the results of trend analysis for each star. For each of the derived parameters, we list the average value as well as the highest significant polynomial degree (*PD*; "–" indicates *no trend* detected). The most obvious result is that for all parameters except period, $>80\%$ of the stars betray time evolution; clearly these LPVs are not constant in their fluctuations. Only about 50% of the stars reveal period evolution; this parameter is significantly more stable than the other five. It is also clear that most of the derived parameters for most of the stars show *complex* trends, as indicated by the high polynomial degree required to model the signal.

Sorting this list in order of period reveals that there is a correlation between period and period variations: longer-period stars are more likely to exhibit fluctuations in period than shorter-period stars. Only 11 of the 33 stars with $P < 407$ days (33%) show period fluctuations, while 16 of 18 (89%) with $P > 407$ do.

Another striking feature which emerges from detailed inspection of individual stars is that fall time and rise time have a *very* strong tendency to evolve oppositely ("mirror evolution"), keeping the period fairly constant. Of 40 stars showing trends in both fall time and rise time, 31 (78%) are "mirrors." In addition, both the period and the maximum magnitude of these stars show significant scatter. Faint maxima tend to be preceded by a longer cycle and followed by a shorter cycle ending in a brighter maximum. This confirms the studies of Harrington (1965) which were done on a much smaller sample of AAVSO data.

In complementary fashion, it is quite common for magnitude at maximum and magnitude at minimum to evolve together ("parallel evolution"). Several of the stars show simultaneous dimming of both maximum and minimum magnitude, which persists for many cycles, followed by recovery of both maximum and minimum magnitudes to their "normal" values.

Table 2 shows those secular trends which are revealed by linear regression. The most notable result is that the carbon LPVs are dimming at maximum magnitude; of 26 stars showing a secular trend in maximum magnitude, all 26 (100%) are getting fainter. It is also clear that for many of the stars, the amplitude is decreasing; of 17 stars showing a secular change in amplitude, 16 (94%) show a decrease. Other noteworthy results are that there is only one star (Z Tau) with significant decrease in period, and only two stars (R Lep and R Cap) show small increases in period.

5. Conclusion

This study establishes beyond doubt that the fluctuations of carbon LPVs tend strongly to exhibit detectable, long-term trends. We have also shown

TABLE 2. Secular Changes

Variable	Total	trend	incr	decr	fastest	increase	fastest	decrease
Period	51	3	1	2	+0.1924	R Lep	–0.7446	Z Tau
Fall time	51	19	10	9	+0.2175	RV Cen	–0.2433	SS Vir
Rise time	51	14	5	9	+0.2890	SS Vir	–0.5034	Z Tau
Max magn.	51	26	26	0	+0.0500	S Cas	———	———
Min magn.	51	18	13	5	+0.0125	S Cas	–0.0101	RU Vir
Amplitude	49	17	1	16	+0.0068	χ Cyg	–0.0386	S Cas

that the trends tend to be of a complex nature, that the period is more stable than the rise time or fall time (so that the light curve *shape* shows significant evolution), and that as a whole, these stars are getting slightly fainter, and their amplitudes are decreasing. Almost certainly, still other overall behavior patterns lie undiscovered. It is also evident that individual stars show a rich variety of interesting behavior, and that many of them merit scrutiny on a case-by-case basis.

We express our sincere gratitude to the many amateur astronomers worldwide who have contributed a wealth of skill, time, and effort to variable star observing. Without their dedication, our knowledge of variable stars would be paltry at best; thanks to their observations, it is possible to study thousands of variables in great detail over nearly a century of observations. This work was partially supported by NASA grant NAGW–1493, for which we are truly grateful. J.A.M. thanks the International Astronomical Union, the American Astronomical Society, and the AAVSO for travel and accommodation grants which made it possible for her to attend this symposium.

References

Campbell, L. 1926, *Harvard Ann.*, v. 79, no. 2
Campbell, L. 1955, *Studies of Long Period Variables*, AAVSO, Cambridge, Massachusetts
Foster, G. 1995, *AJ*, 109, 1889
Foster, G. 1996a, *AJ*, 111, 541
Foster, G. 1996b, *AJ*, 111, 555
Foster, G. 1996c, *AJ*, 112, 1709
Harrington, J.P. 1965, *AJ*, 70, 569
Mattei, J.A., Mayall, M.W. & Waagen, E.O. 1990, *Maxima and Minima of Long Period Variables 1949–1975*, AAVSO, Cambridge, Massachusetts

Discussion

Wing: Can you say whether temporary decreases in amplitude, such as you illustrated in the cases of several C and S stars, also occur in M-type variables?

Mattei: We have not yet carried out a thorough trend analysis for the M stars, so I cannot comment about them. We will do that analysis next.

Ake: I'd like to point out that W Aql is a binary star. There is a short paper by Herbig in 1965 where he reports that a G–type spectrum is revealed at minimum light.

Mattei: I'd be very interested in that reference. [It is: Herbig, G.H. 1965, in 3rd *Colloquium on Variable Stars*, Kleine Veröffentlichungen der Remeis-Sternwarte Bamberg, vol. 4, no. 40, p. 164 –Ed.]

Fernie: Where Miras show long-term trends in period, are these predominantly increasing or decreasing?

Mattei: Only 3 stars show secular change in period (Z Tau, R Lep, R Cap). Two others show a possible secular change. Of the 5 possible changes, 2 show a period decrease and 3 a period increase. However, only one trend (Z Tau) is a strong period decrease.

Frogel: For the stars that show a decrease in period and amplitude, do these quantities still lie on the mean relation between period and amplitude for all stars?

Mattei: Yes – the decrease in amplitude and period is episodic, not overall.

Frogel: Very little luminosity comes out in the V bandpass for LPVs. Molecular blanketing dominates the spectrum. So small changes in blanketing could cause, in part, the temporary decreases in amplitude observed, although it isn't obvious how this would affect the period.

Mattei: True. One may explain shorter period and smaller amplitude if luminosity is lowered. However, the timescales for this are much, much longer than the timescales we are seeing, which are between 6 and 15 years in the four stars I mentioned.