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GRAPHICAL CHARACTERIZATION OF RV TAURI LIGHT CURVES

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Abstract

A graphical technique for characterizing the light curves of RV Tauri variables is described. It is based on three measurements which are combined into two ratios plotted one against the other. Points that fall close together on the graph have similar light curves and also seem to share other properties in common (e.g., period); this suggests that the technique might be useful for classifying members into subclasses. The scatter of points corresponding to individual cycles can be used as a measure of cycle regularity.

* * * * *

1. Introduction

RV Tauri stars are relatively rare pulsating semiregular variables that are transitional between Cepheids and long period Mira variables. Membership in the RV Tauri class is generally based on spectral type (F, G, K, and as late as M during minimum light), period (50-150 days), and the character of the light curve (Dawson 1979). The light curve is generally cyclic and quite distinctive, characterized by alternating deep and shallow minima separated by maxima of approximately equal brightness, with a tendency for the maxima following deep minima to be slightly brighter. The light curve for the star AC Her is a good example of a 'well behaved' RV Tauri variable. See Figure 1.

It is generally recognized that RV Tauri stars are not a homogeneous group (Dawson 1979; DuPuy 1973). Frequent monitoring of 13 relatively bright members of the group which are the subject of this study demonstrated this. Table I identifies these 13 stars. From the standpoint of the light curves, the most obvious differences are between the RVa types, whose mean brightness is relatively constant, and the RVb types, whose mean brightness changes over several years and many cycles. AC Her is an example of an RVa type (see Figure 1), and other members of this subgroup are noted in Figures 2 and 3, along with their smoothed light curves. Smoothed light curves in this paper are based on my observations which are on file at AAVSO Headquarters.

In addition to the distinction between RVa and RVb types, more subtle differences are noted in the basic cyclic pattern. The purpose of this study is to draw attention to these subtle differences and to introduce a graphical method for distinguishing them. The hope is that this graphical method will help to identify genetically related members and lead to a more refined classification. At the very least, the graphs visually document the degree of uniformity of the light curves from cycle to cycle.

2. Measurements Needed to Prepare Graph

An RV Tauri light curve will be characterized by three measurements. See Figure 5. The first step in the measurement procedure is to draw a succession of horizontal baselines corresponding to the magnitude of each deep minimum; each baseline extends only to the next deep minimum. Magnitude differences between each baseline and

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1987JAVSO..16...71H

the two following maxima are recorded. The first maximum after the primary or deep minimum is designated the primary peak (pp), the next maximum is the secondary peak (sp). Corresponding magnitude differences are labeled Δmpp and Δmsp respectively. Usually Δmpp>Δmsp, but occasionally the secondary peak is brighter. The decision to draw the baseline from the preceding deep minimum instead of the following one is arbitrary.

The third measurement characterizes the shallower secondary minimum (sm). It is obtained by drawing a line tangent to the two maxima and measuring the magnitude difference between the point of secondary minimum and this line. The measurement is labeled Δmsm.

The idea of describing an RV Tauri light curve by three measurements is not new. Tsesevich (1975) used a slightly different basis for obtaining his measurements, but instead of using them to characterize the light curve, he employed them in a vain attempt to relate light curve amplitudes to velocity variations.

The three measurements are next combined to form two ratios so that the results can be displayed graphically. See Figure 6. Approximate, corresponding shapes of light curves are sketched on Figure 6 to illustrate the significance of the ratios. Two trends are noted: secondary minima become deeper to the right, and secondary maxima become brighter toward the top.

If the light curves were represented by two sine curves - a fundamental with amplitude Af and period P, and a harmonic with amplitude Ah, period P/2, and relative phase angle ϕ - then the magnitude m as a function of time t would be expressed as

$$m = Af \sin(2\pi t/P) + Ah \sin(4\pi t/P + \phi). \tag{1}$$

One could then relate the two measured ratios Δmsp/Δmpp and Δmsm/Δmpp to the ratio Ah/Af and the phase angle ϕ. The fan-shaped overlay appearing on Figure 7 allows one to read Ah/Af and ϕ when the measured ratios are plotted. The overlay should give good estimates of the curve parameters (i.e., Ah/Af and ϕ) if the light curve is composed chiefly of a fundamental sine curve and its first harmonic. In such cases the graphical method could be a simple substitute for a Fourier harmonic analysis, a mathematical technique designed to decompose a periodic curve into its harmonic components.

3. Graphical Distribution of Points Representing Light Curves

Light curves from the 13 variables listed in Table I were examined in this study. I have been observing these stars for from nearly two to as many as five years at a frequency of one to three days, weather permitting. Gaps over 10 days are rare outside of seasonal solar conjunctions. Measured magnitude differences and calculated ratios are listed in Table II. Average ratios for each star are also listed in this table, and these are the values plotted in Figure 8.

Stars lying close together on the graph have similar light curves because the measurements characterize the basic shape of the curve. If neighboring stars also have other attributes such as period or behavior in common, the graph might be helpful in classifying members into subgroups which may be genetically related. Indeed, there are some groupings which lend encouragement to this possibility.

The stars R Sge and V Vul which lie close together have similar curves (see Figure 2) and periods (71 and 76 days, respectively). AC Her with a period of 76 days falls nearby too, and all three seem to be fairly regular. The stars V360 Cyg and CT Ori with deep secondary minima lie in the upper-right part of the graph and have similar

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1987JAVSO..16...71H

periods of 71 and 66 days, respectively. According to Figure 7, these stars are probably pulsating primarily in a harmonic mode. The stars SU Gem and DF Cyg located in the lower-right part of the graph have the shortest period of all, 50 days, but more significantly, both are prime examples of the RVb subgroup with long period variation in their average brightness. See Figure 4. Cycles with small amplitudes occurring during extended dim periods were not included when computing the magnitude ratios for these RVb types.

It may be significant that SU Gem and DF Cyg which have the shortest periods are plotted in the lower right, whereas R Sct with the longest known period of 144 days is plotted at the upper left. The diagonal band from upper right to lower left includes the other stars whose periods range from 66 to 90 days.

Not all stars relate to their neighbors on the plot. UZ Oph manifests irregularities and at times behaves like a Cepheid (see Figure 3), yet it falls close to the fairly regular AC Her in Figure 8. Interestingly, other members exhibiting irregular behavior and/or occasional interchange of deep and shallow minima, such as TW Cam, RV Tau, U Mon, and TT Oph (see Figures 3 and 4), lie in more-or-less the same region of the graph. No attempt was made to characterize the light-curve shapes when non-RV Tauri behavior was evident, and this in part explains why the plotted points for these stars are based on fewer measurements (see Table II).

In order to check the accuracy of the graphical method for estimating the amplitude ratio Ah/Af, a Fourier harmonic analysis was performed on the light curves for two stars with numerous observations spanning several cycles. The frequency spectrum for R Sct in Figure 9 shows that two frequencies dominate, a fundamental with a 141.8-day period (Af = 0.48) and a first harmonic with a 70.9 day period (Ah = 0.29); the ratio Ah/Af is equal to 0.60, in good agreement with the average value plotted in Figure 8. The spectrum for TT Oph (see Figure 10) is dominated by the first harmonic with a 30.7-day period (Ah = 0.26). The fundamental with a 61.4-day period (Af = 0.08) is weak and nearly rivalled in amplitude by two higher-order harmonics (corresponding to the 1/21 and 1/28 fractions of the 430-day interval involved in the Fourier analysis). The amplitude ratio for TT Oph based on the Fourier analysis is 3.25, which is higher than the average plotted value (1.6) in Figure 8. The higher-order harmonics are probably responsible for the difference.

The graphical display may also be employed to judge the uniformity of light-curve shapes from cycle to cycle. Individual cycles are plotted in Figure 11 for three stars. Note the relatively tight clustering of points from the AC Her cycles, which lends support to the earlier statement that AC Her is a 'well behaved' member of the clan. In contrast, points for the TT Oph and R Sct cycles (note outlying point at lower left) exhibit more scatter, implying that their pulsational behavior is less regular.

Before concluding, we should take note of the potential for relatively large errors in plotted values owing to the limited accuracy in visually estimating magnitudes. An estimation error of 0.1 magnitude can lead to a ten percent error in magnitude ratio if the brightness range is only one magnitude. For this reason, averaged values plotted in Figure 8 are not very reliable if they are based on only a few cycles. Photometric measurements could reduce this error and need be scheduled only during minima and maxima, since it is the magnitudes corresponding to those times that determine the plotted ratios.

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4. Conclusions

A simple procedure for quantifying the shapes of RV Tauri light curves and graphically plotting the results can reveal the degree of regularity and similarity in the basic pulsational cycle. There are hints that stars lying close together on the graph have other attributes such as period and general behavior in common, and it is possible that genetic subgroups might be revealed through this technique. However, since some stars do not relate to their neighbors on the plot, and observational errors in magnitude estimates contribute to data scatter, it is premature to draw any firm conclusions. More data, especially photometric measurements strategically timed at minima and maxima, would be helpful in evaluating the technique. At the very least, the graphical technique can be used to judge cycle repeatability by examining the degree to which points representing individual cycles scatter on the graph.

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TABLE I

RV Tauri Variables Examined in This Study*

Variable	Type	Mag. Range	Period	Comments
TW Cam	RVa	9.4 - 10.5	87d	Occasional irregularities
RV Tau	RVb	9.1 - 10.6	79	RVb behavior subtle
SU Gem	RVb	9.9 - 12.4	50	
CT Ori	RVa	10.1 - 11.3	66	Period from Horowitz (1986)
U Mon	RVb	5.6 - 8.0	92	
TT Oph	RVa	9.5 - 11.2	61	Phase shifts noted
UZ Oph	RV	10.1 - 12.5	87	Irregularities common
R Sge	RVb	8.7 - 10.1	71	I question RVb designation
AC Her	RVa	7.2 - 8.7	75	Good repeatability among cycles
R Sct	RVa	4.7 - 8.6	144	Long period for RV Tauri star
DF Cyg	RVb	10.0 - 13.2+	50	
V Vul	RVa	8.2 - 10.0	76	Good repeatability among cycles
V360 Cyg	RVa	10.7 - 11.8	70	

*Type designation and period from Dawson (1979), unless noted. Visual magnitude range and comments based on my observations.

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1987JAVSO..16...71H

TABLE II

Measured Magnitude Differences and Calculated Ratios

Star	Approximate Cycle Dates (2400000+)	Δmpp	Δmsp	Δmsm	Δmsp/Δmpp	Δmsm/Δmpp
TW Cam	46460 - 46540	0.75	0.75	0.55	1.000	0.733
	46635 - 46720	1.00	0.90	0.40	0.900	0.400
	46720 - 46800	0.90	0.90	0.30	1.000	0.333
					avg 0.967	**0.489**
DF Cyg	46640 - 46700	1.40	1.20	1.00	0.857	0.714
	46700 - 46740	1.50	1.30	1.10	0.867	0.733
	46900 - 46940	1.40	1.10	0.85	0.786	0.607
					avg 0.837	**0.685**
V360 Cyg	46650 - 46720	0.90	1.00	0.75	1.111	0.833
	46870 - 46930	0.90	0.90	0.70	1.000	0.778
	46930 - 47010	0.80	0.90	0.65	1.125	0.722
	47010 - 47080	0.70	0.70	0.60	1.000	0.857
					avg 1.059	**0.798**
SU Gem	46375 - 46440	1.80	1.70	1.25	0.944	0.694
	46440 - 46490	2.00	1.90	1.75	0.950	0.875
	46490 - 46540	1.50	1.30	1.30	0.867	0.867
					avg 0.920	**0.812**
AC Her	45530 - 45600	1.60	1.35	0.70	0.844	0.438
	45900 - 45980	1.35	1.30	0.60	0.963	0.444
	45980 - 46050	1.50	1.40	0.40	0.933	0.267
	46130 - 46210	1.15	1.00	0.30	0.870	0.261
	46210 - 46280	1.50	1.30	0.50	0.867	0.333
	46280 - 46350	1.30	1.20	0.35	0.923	0.269
	46350 - 46430	1.30	1.10	0.45	0.846	0.346
	46430 - 46510	1.10	1.00	0.55	0.909	0.500
	46510 - 46580	1.40	1.30	0.50	0.929	0.357
	46580 - 46660	1.40	1.30	0.55	0.929	0.393
	46660 - 46730	1.30	1.05	0.35	0.808	0.269
	46890 - 46960	1.40	1.40	0.40	1.000	0.286
	46960 - 47030	1.50	1.30	0.60	0.867	0.400
	47030 - 47110	1.40	1.30	0.55	0.929	0.393
					avg 0.901	**0.354**
U Mon	45640 - 45730	1.55	1.50	0.40	0.968	0.258
	45730 - 45820	1.20	1.10	0.40	0.917	0.333
					avg 0.943	**0.296**
TT Oph	46220 - 46280	1.40	1.40	0.50	1.000	0.357
	46280 - 46340	1.50	1.60	0.75	1.067	0.500
	46465 - 46520	1.30	1.10	0.50	0.846	0.385
	46520 - 46580	1.10	1.10	0.50	1.000	0.455
	46620 - 46680	1.30	1.20	0.95	0.923	0.731
	46680 - 46740	1.50	1.50	0.70	1.000	0.467
	46800 - 46860	1.60	1.60	0.80	1.000	0.500
	46860 - 46920	1.20	1.00	0.90	0.833	0.750
	46920 - 46980	1.30	1.20	0.85	0.923	0.654
					avg 0.955	**0.533**
UZ Oph	46270 - 46340	1.80	1.40	0.55	0.778	0.306
	46570 - 46650	1.80	1.60	0.90	0.889	0.500
	46830 - 46900	1.55	1.50	0.40	0.968	0.258
	46920 - 47000	2.30	2.30	1.20	1.000	0.522
	47000 - 47080	2.40	2.20	0.60	0.917	0.250
					avg 0.910	**0.367**

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1987JAVSO..16...71H

TABLE II (cont'd)

Measured Magnitude Differences and Calculated Ratios

Star	Approximate Cycle Dates (2400000+)	Δmpp	Δmsp	Δmsm	Δmsp/Δmpp	Δmsm/Δmpp
CT Ori	46405 - 46470	1.00	1.00	0.90	1.000	0.900
	46470 - 46540	0.90	1.00	0.75	1.111	0.833
	46670 - 46730	1.00	0.90	0.75	0.900	0.750
	46800 - 46865	0.80	0.70	0.45	0.875	0.563
	46865 - 46930	0.90	0.90	0.50	1.000	0.555
	47070 - 47140	0.90	0.90	0.50	1.000	0.555
					avg 0.981	**0.693**
R Sct	45430 - 45580	2.90	2.90	0.90	1.000	0.310
	45720 - 45860	2.50	2.35	0.60	0.940	0.240
	45860 - 46010	2.80	2.40	0.95	0.857	0.339
	46160 - 46280	3.10	3.30	0.50	1.065	0.161
	46280 - 46440	3.30	3.20	0.45	0.970	0.136
	46440 - 46580	2.45	2.40	0.80	0.980	0.327
	46580 - 46720	1.70	1.05	0.15	0.618	0.088
	46880 - 47020	3.50	3.30	0.70	0.943	0.200
	47020 - 47160	2.50	2.40	0.70	0.960	0.280
					avg 0.926	**0.231**
R Sge	46620 - 46690	1.20	1.10	0.25	0.917	0.208
	46690 - 46760	0.90	0.70	0.40	0.778	0.444
	46830 - 46910	1.20	1.10	0.25	0.917	0.208
	46910 - 46980	1.30	1.00	0.35	0.769	0.269
	46980 - 47050	1.20	1.10	0.25	0.917	0.208
	47050 - 47120	1.20	1.00	0.20	0.833	0.167
					avg 0.855	**0.251**
RV Tau	46060 - 46140	1.30	1.30	0.80	1.000	0.615
	46330 - 46420	0.90	0.80	0.70	0.889	0.778
	46420 - 46500	0.80	0.70	0.60	0.875	0.750
	46700 - 46780	1.00	0.90	0.55	0.900	0.550
	46780 - 46850	0.90	0.90	0.30	1.000	0.333
	46850 - 46940	1.10	1.20	0.95	1.091	0.864
	47010 - 47080	1.10	1.00	0.45	0.909	0.409
					avg 0.952	**0.614**
V Vul	46240 - 46320	1.30	1.05	0.35	0.808	0.269
	46320 - 46400	1.25	1.10	0.10	0.880	0.080
	46400 - 46470	1.20	1.10	0.15	0.917	0.125
	46470 - 46540	1.50	1.20	0.35	0.800	0.233
	46540 - 46620	1.40	1.10	0.15	0.786	0.107
	46620 - 46700	1.40	1.20	0.55	0.857	0.393
	46700 - 46780	0.90	0.70	0.20	0.778	0.222
	46850 - 46930	1.50	1.40	0.45	0.933	0.300
	46930 - 47000	1.50	1.40	0.35	0.933	0.233
	47000 - 47080	1.25	1.15	0.70	0.920	0.560
					avg 0.861	**0.252**

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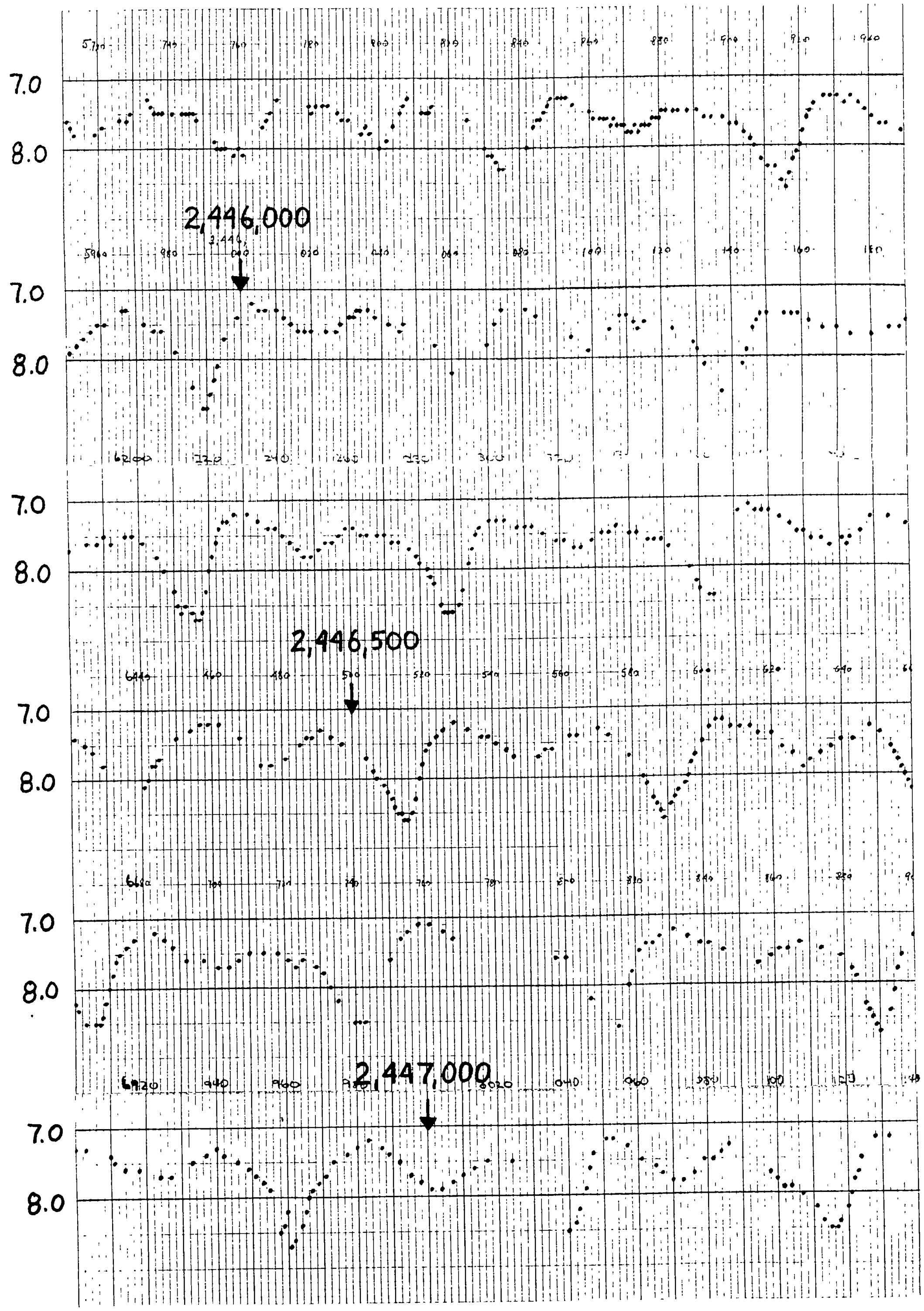

Figure 1. Light curve for AC Her, a fairly regular RV Tauri variable belonging to subgroup RVa.

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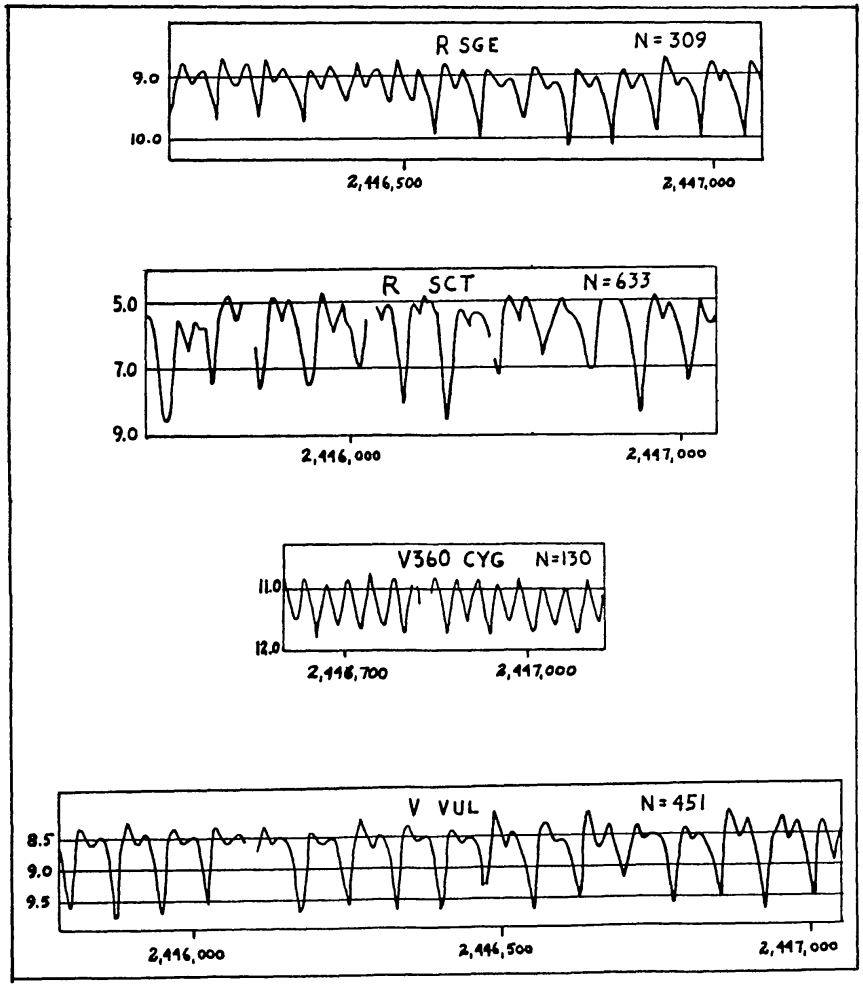

Figure 2. Smoothed light curves for RV Tauri variables included in study and belonging to subgroup RVa. (N = number of observations used to draw curve.)

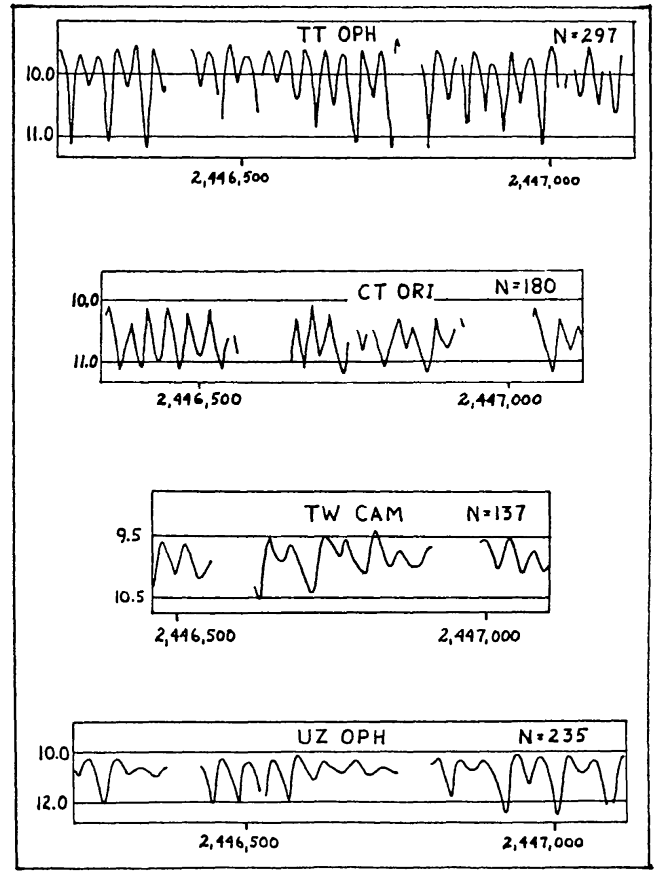

Figure 3. Smoothed light curves for RV Tauri variables included in study and belonging to subgroup RVa. (N = number of observations used to draw curve.)

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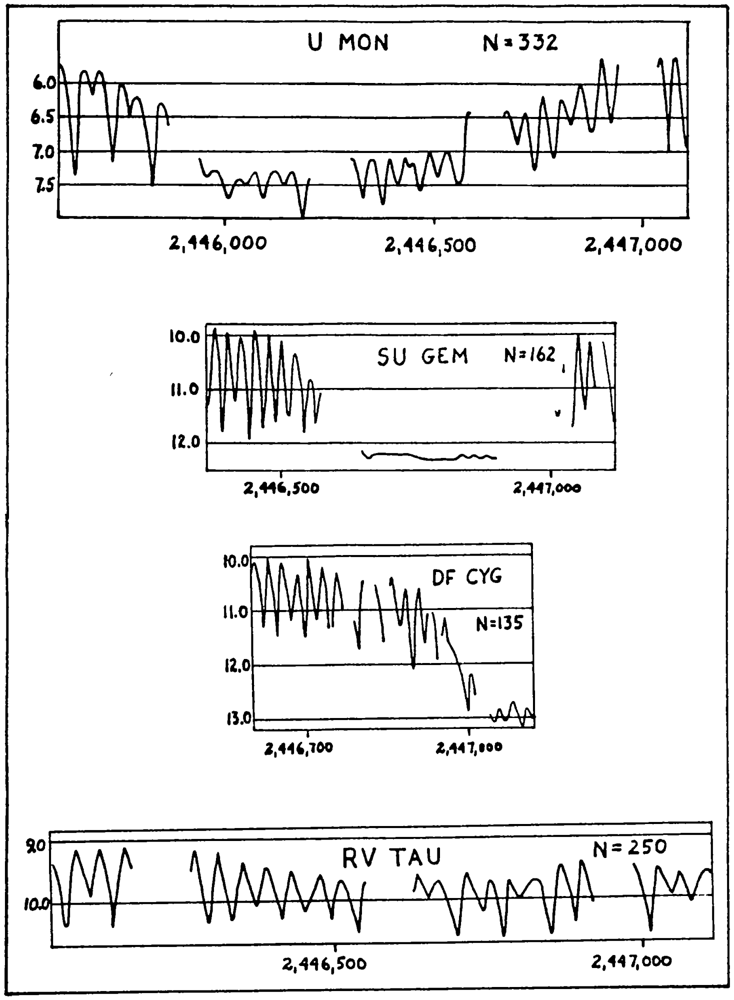

Figure 4. Smoothed light curves for RV Tauri variables included in study and belonging to subgroup RVb. (N = number of observations used to draw curve.)

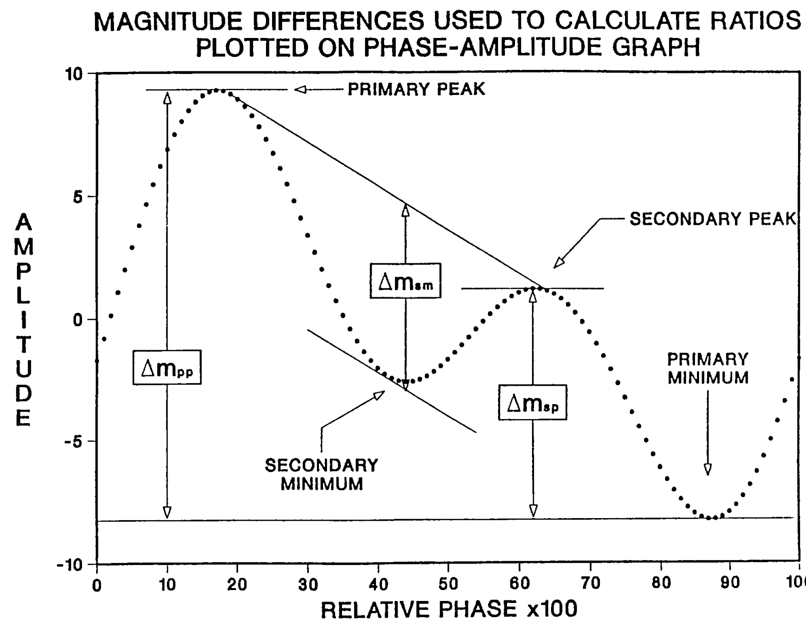

Figure 5. Definition of magnitude differences (Δmpp, Δmsp, Δmsm) measured from light curves.

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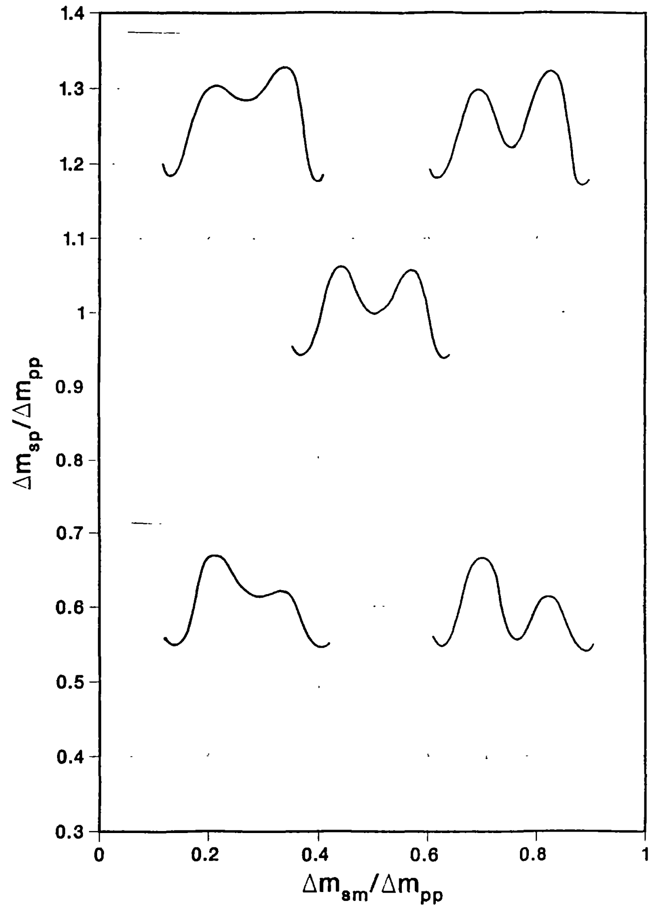

Figure 6. Graph used to plot ratios characterizing RV Tauri light curves. Sketches illustrate the shapes of light curves associated with different areas of the graph.

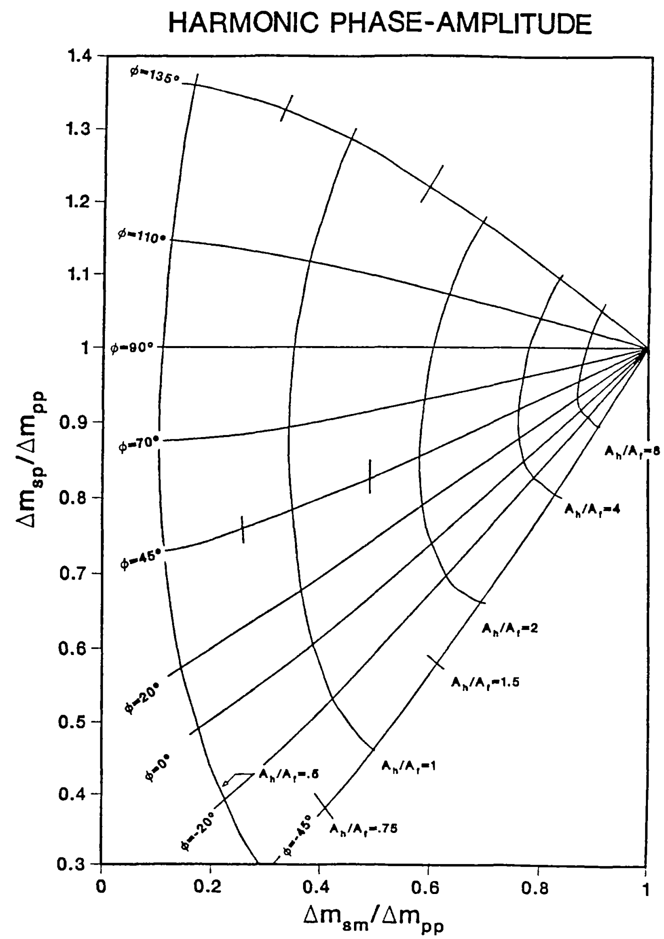

Figure 7. Overlay for estimating the amplitude ratio (Ah/Af) and phase angle (ϕ) for light curves represented by Equation (1) in the text.

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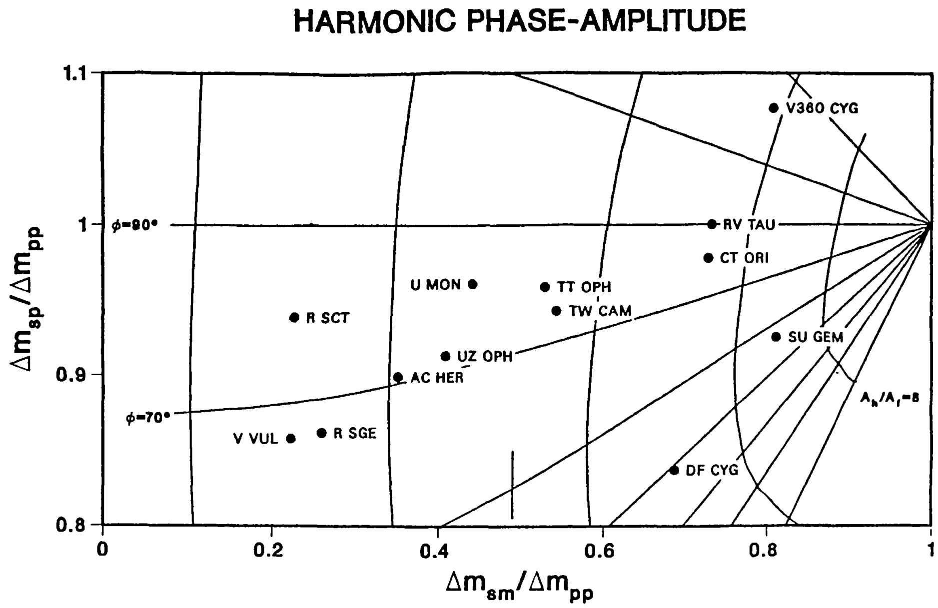

Figure 8. Scatter plot of average amplitude ratios characterizing the light curves of selected RV Tauri variables.

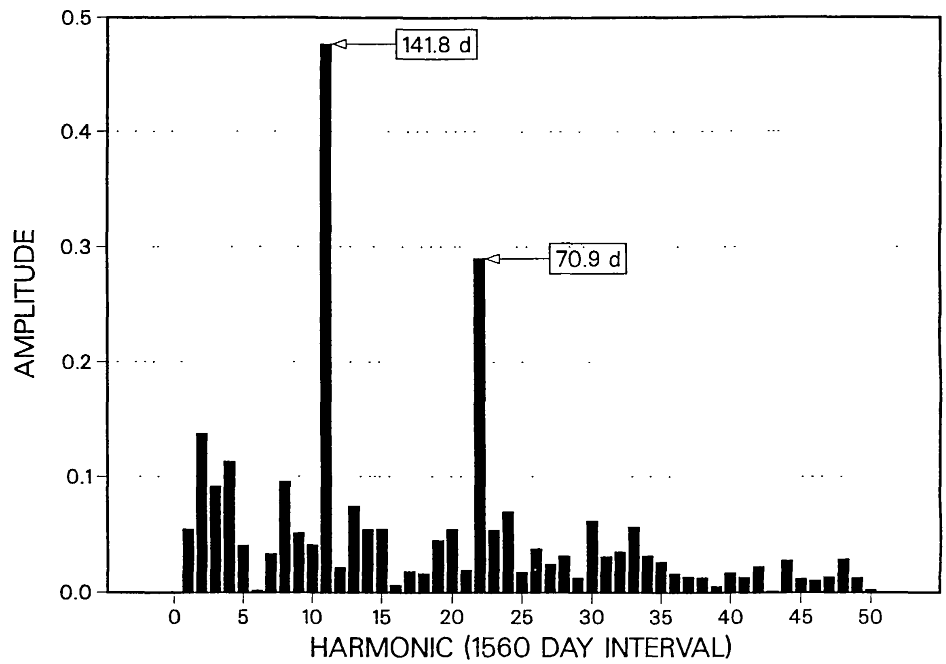

Figure 9. Discrete Fourier transform of the light curve from R Sct (period represented from JD2445400 to 2446980).

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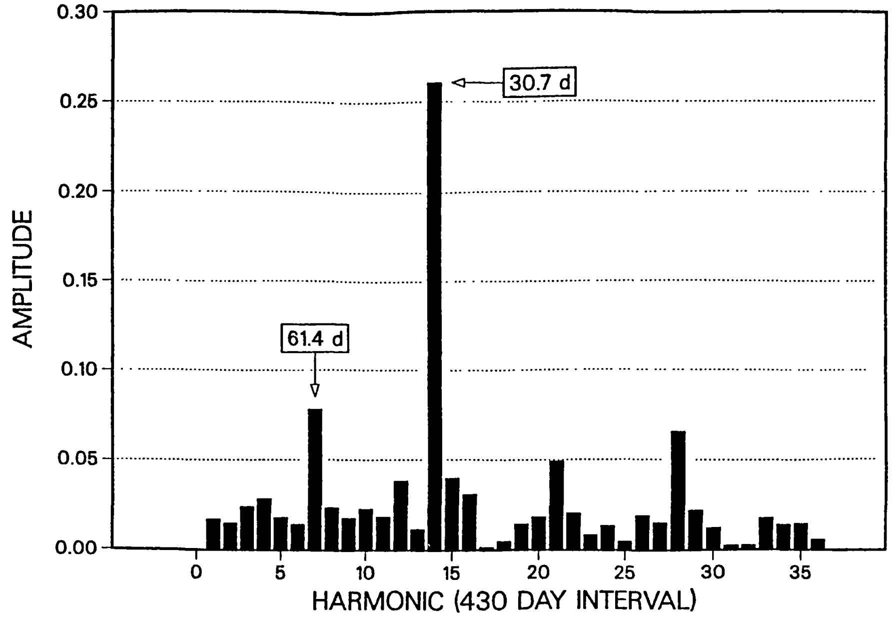

Figure 10. Discrete Fourier transform of the light curve from TT Oph (period represented from JD2446570 to 2447000).

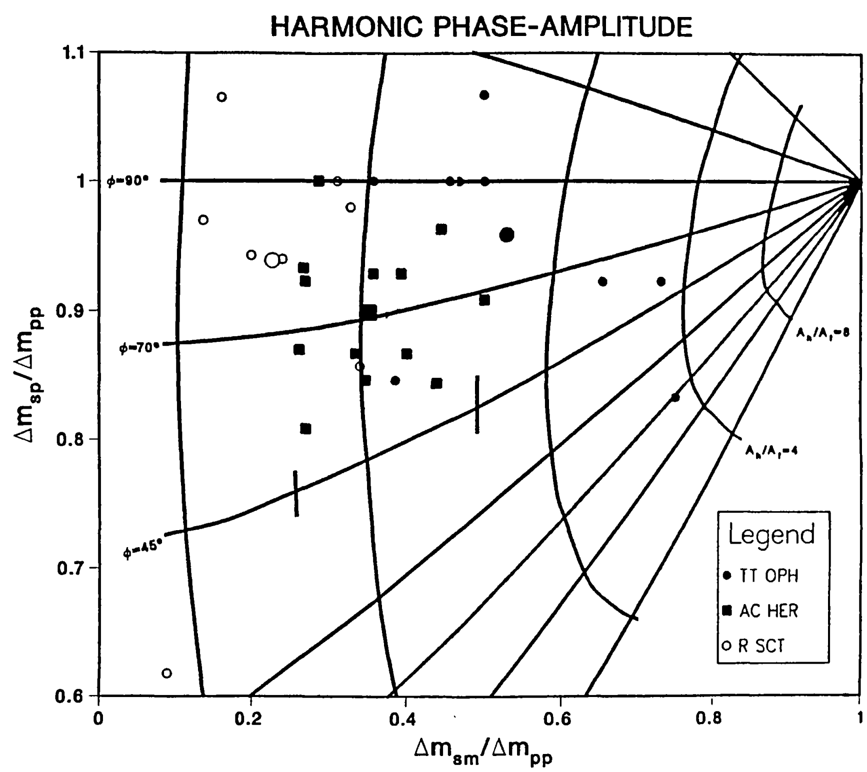

Figure 11. Scatter plot of amplitude ratios for individual cycles of three RV Tauri variables (AC Her, TT Oph, R Sct). Larger symbols represent the average value for the corresponding star.

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