Studies of "Irregularity" in Pulsating Red Giants. III. Many More Stars, an Overview, and Some Conclusions

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Abstract We have analyzed AAVSO visual observations of an additional 85 "irregular" (L-type) pulsating red giants, using Fourier and self-correlation analysis; see *JAAVSO,* **37**, 71 (2009) and *JAAVSO,* **38**, 161 (2010) for details of the methods and previous results. We have categorized the variability of each star (periodic/semiregular, irregular, or not significantly variable), and noted the presence of various spurious effects arising from the visual observing process. Finally, we have suggested which stars should be highest priority for further visual or photoelectric observation, and which could reasonably be dropped from the visual program, and why.

1. Introduction

Cool red giants are all variable in brightness. They are classified in the *General Catalogue of Variable Stars* (*GCVS*, Kholopov *et al.* 1985) as Mira (M), semiregular (SR), or irregular (L). In previous papers (Percy *et al.* 2009, Percy and Long 2010, hereinafter Papers I and II), we showed, through self-correlation and Fourier analysis of AAVSO visual observations, that the L-type variables show a spectrum of behavior, from truly irregular, to semi-periodic. We also found evidence of spurious one-year and one-sidereal-month periods in some of the stars, presumably due to a physiological phenomenon called the Ceraski effect, which arises from the methodology of visual observation. The purpose of the present paper is to extend our analysis to L-type red giants in the AAVSO visual observing program which have fewer observations than those in Papers I and II. All of these stars were presumably placed on the AAVSO visual observing program because they had been found or suspected to be variable, and required study and classification, all of them have already been classified, on some basis, as being or suspected of being irregular (L, Lb, Lc types).

2. Data and analysis

Please see Papers I and II for a description of the visual data, which are taken from the AAVSO International Database, and the two methods of analysis—Fourier (using PERIOD04), and self-correlation—and for examples of Fourier spectra and self-correlation diagrams. Dr. Matthew Templeton, Science Director, AAVSO Headquarters, kindly provided us with a list of all L-type stars in the database, listed in order of decreasing number of observations. The numbers of observations of the stars in Paper II range from 19,863 down to 3,642. In this paper, the numbers range from 2,683 (AO Cru) down to 249 (NSV 13234). The stars U And, TT Leo, and TY Oph, from Papers I and II, were re-analyzed, with similar results (Table 1).

Some of the stars also had some photoelectric or CCD observations but, for consistency, we used visual data only.

3. Results

The results of the analysis are summarized in Table 1. The columns in Table 1 give: the star name; the variable star type, spectral type, and range (from SIMBAD); the number N of observations; Δm(0) and Δm(4000); and comments about true or spurious periods. The symbol in brackets after the range is the wavelength band to which the range applies. Δm(0) is the intercept on the vertical axis of the self-correlation diagram; it is a measure of the average observational error in the data. Δm(4000) is the average Δmag at Δt = 4,000 days in the self-correlation diagram, and is a measure of the variability (including observational error) on time scales of up to this value. The difference between Δm(4000) and Δm(0) is a measure of the true variability. In the Comments column: Y and M indicate a signal at a period of one year or one sidereal month, respectively. As usual, a colon (:) denotes uncertainty.

The value of Δm(0) depends on several factors, including the brightness of the star and the quality of the comparison sequence. For instance: one observer points out that the comparison stars for KK Per are not conveniently situated, which may explain its Δm(0) of 0.30—significantly higher than for other sixth-magnitude variables. As always, the quality of the visual data could probably be improved by re-examining the sequences of comparison stars. AAVSO Headquarters has invested considerable time and effort in improving observing charts and comparison star magnitudes in the last decade.

Several stars show a phenomenon that we have occasionally seen in the self-correlation diagrams of stars in Papers I and II (W CMa, WY Gem, TX Per, and DY Vul, for instance): very weak minima at Δt = ~200 + 365 N days, where N is an integer. The amplitudes, however, are less than 0.02 magnitude. We suspect that this is a spurious effect—the Ceraski effect or something similar—related to the method of observation, the lengths of the seasons and of the seasonal gaps, both of which are ~200 days long. In the Comments column of Table 1, we have denoted this by "200/550."

Some stars show real periods. These are denoted by PN(A) where N is the period in days, and A is the amplitude—half the peak-to-peak range. The periods shorter than a few hundred days are probably due to pulsation. Longer periods may be so-called "long secondary periods"; their nature is still not known (Nicholls *et al.* 2009). Stars considered to be not significantly variable are denoted "nsv"; in practice, this means that the visual amplitude is less than about 0.04 magnitude. Those which are variable but without discernible periodicity are denoted "irr." (irregular).

4. Which irregular red giants should continue to be observed, and how?

There are several thousand stars on the AAVSO visual observing program, including over 900 irregular red variables, according to the list from AAVSO Headquarters. Most have only a handful of observations. Based on the results of this paper, and Papers I and II, we can make recommendations about which stars should continue to be observed, and how (Table 2). These are our recommendations, and not necessarily those of AAVSO staff.

Why observe irregular red variables in the first place? One reason is to confirm that they are variable, and to estimate their amplitude, and to classify them. If they are periodic or semiregular, it is important to determine their period(s), since the period(s), and any changes therein, can provide additional information about the star. Even if the star is not periodic, self-correlation can provide a "profile" of the variability—the amount of variability as a function of time scale—as discussed in Papers I and II.

The advantage of the visual observations in the AAVSO International Database is that they have been made consistently over a long period of time. They can illuminate the stars' variability on time scales from days to decades. This is important in the case of red giants, in which variability is known to occur on these time scales.

A few L-type red giants are known to be complex and interesting. TZ Cyg, for instance, is multi-periodic. It is being analyzed in detail by Dr. Templeton. We did a cursory analysis of this star, but have not included it in Table 1.

We should first point out that, for the stars with the smallest number of observations (a few hundred), the results of the time-series analysis, i.e. the reality, value, and amplitude of any suspected periods, real or spurious, was uncertain. Many more long-term (visual) observations would be required to be sure. We question whether such observations would be worthwhile. Therefore we do not recommend that sparsely-observed L-type red variables (those with less than about 250 observations) should continue to be observed visually, unless there is some exceptional reason to do so.

This having been said, here is what we have found out about irregular red variables in the AAVSO International Database. Note that all of these stars have already been classified as L type.

Some stars show little or no significant variability ("nsv"), and no discernible real period. Visual observation of these stars can be discontinued. Many stars show irregular variability ("irr."), with no discernible real periods. Our analysis has provided a "profile" of the variability, and it is doubtful that this profile will change. Visual observation of these stars can also be discontinued, though there is always a small chance that the behavior of the star, or properties such as mean magnitude, could change in future.

Some stars show discernible real periods, usually with amplitudes of a few hundredths of a magnitude. Further observations may refine the periods, or provide information about changes in the period or amplitude. In Table 2, we have divided these stars into three groups: (i) higher-priority stars which show definite evidence of periodicity, usually with an amplitude of 0.1 magnitude or more, which could provide useful information about the star—even with visual observations; (ii) medium-priority stars for which there is some evidence for periodicity (albeit usually of low amplitude); and (iii) lower-priority stars which are borderline, and could be dropped from the visual program. These and group (ii) are possible candidates for photoelectric or CCD observing. Our groupings are arbitrary; there is a continuous spectrum of behavior in L-type variables, from strong, large-amplitude periodicity (which definitely warrants continued observation) to weak, low-amplitude, marginal behavior.

Most of the stars with discernible periods have small amplitudes. Using time-series analysis, however, it is possible to extract small-amplitude periods from visual data, e.g. Percy and Palaniappan (2006), who clearly detected low-amplitude rotational variability in AAVSO visual observations of T Tauri stars. Long-term photoelectric photometry would obviously be better but, as noted below, we question the value of long-term photometry for these stars, especially the fainter ones.

Some of the "not significantly variable" stars, and most of the stars in group (iii) may actually be microvariables; the variability of the brighter stars could be studied with photoelectric photometry. The variability of bright small-amplitude red variables, however, has already been well-studied, including by the AAVSO Photoelectric Photometry Program (Percy *et al.* 2008 and references therein). Furthermore, tens of thousands of small-amplitude red variables have already been discovered and studied in survey projects such as MACHO and OGLE. Nevertheless, there is value in continuing to observe bright, periodic, small-amplitude red giants, since these stars can also be studied using other techniques such as spectroscopy and interferometry.

6. Discussion and conclusions

In addition to the spurious one-year and one-month periods discussed in Papers I and II, which we assume are due to the Ceraski effect, we have identified another apparently-spurious, low-amplitude effect: minima in the self-correlation diagram at Δts of ~200 + 365 N days. Many of the stars in Table 1 show one or more of these spurious effects, though it is difficult to confirm them in stars with fewer observations.

In this and Papers I and II, we have analyzed all of the irregular red giants in the AAVSO visual program that have about 250 or more observations. While analysis of stars with fewer observations might conceivably yield some results, that is unlikely, partly because the observations are so sparse, partly because they would have to be sustained over many years, and partly because the stars with more observations tend to be ones for which there is some a priori reason to believe that they may be interesting, for example, they show some evidence of periodicity.

We have also raised some interesting questions about priorities for visual observing of stars in the AAVSO International Database. These are questions that should be considered by AAVSO staff and observers. The question of "which stars to observe" depends on both the scientific value of the observations, on the interests and expertise of the observers, and on the amount of data already accumulated. We will leave it to AAVSO Headquarters to decide on the strategies and priorities for visual and/or CCD observing of these stars.

The analysis of the stars in Table 1 supports the main conclusion of Papers I and II: L-type variable red giants show a continuous spectrum of behavior, from not significantly variable, to irregular, to marginally periodic, to semiregular. The analysis also shows the value of systematic, long-term visual observations of variable stars: for each of the stars in our sample, we have been able to derive some conclusion about its variability, even if the result is a negative one.

8. Acknowledgements

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Table 1. Results of time-series analysis of L-type red giant variables.

Star	*Type*	*Spectrum*	*Range*	*N*	*Dm (0)*	*Dm (4000)*	*Comments*
AO Cru	Lc	M0Ia/ab	8.5–10.0 (p)	2683	0.38	0.37	200/550; nsv
V930 Cyg	Lb	—	12.9–13.9 (p)	2658	0.44	0.61	P250(0.3)
V1152 Cyg	Lb	M6D	13.0–14.3 (p)	2397	0.16	0.34	200/550; irr.
ψ1 Aur	SRc	K5Iab	4.68–5.02 (V)	2368	0.18	0.27	Y:, P175(0.02), P2000(0.09:)
BO Car	Lc	M4Ib	7.18–8.5 (V)	2160	0.40	0.55	200/550, irr.
V451 Cas	Lb	M5	9.3–10.0 (p)	2059	0.37	0.45	Y:, irr.
KK Per	Lc	M1–3.5Iab	6.6–7.89 (V)	1909	0.30	0.33	nsv
κ Oph	Lb:	K2III	4.1–5.0 (p)	1842	0.16	0.23	Y:, irr.
PR Per	Lc	M1Iab/b	9.8–10.8 (p)	1828	0.32	0.36	Y: P2730 (0.02), irr.
ZZ Cam	Lb	M0–5	8.7–9.3 (p)	1670	0.17	0.21	Y, irr/nsv:
PP Per	Lc	M0–1.5Ia/ab	9.1–10.3 (V)	1610	0.29	0.33	Y:, nsv
V391 Cas	Lb	M4	9.2–10.0 (p)	1526	0.13	0.14	P393(0.02)
RX Cru	Lb:	C(N:)	15–16 (p)	1435	0.28	0.62	P280(0.2:), P548(0.3:)
AS Cep	Lb	M3	11.3–12.9 (p)	1335	0.25	0.35	200/550:, Y:, irr.
BI Cyg	Lc	M4Iab	8.4–9.9 (p)	1329	0.45	0.57	P300(0.03):
HK Lyr	Lb	C6,4(N4)	7.8–9.6 (V)	1289	0.27	0.54	Y, irr.
ε Peg	Lc	K2Ib	0.7–3.5 (V)	1281	0.20	0.27	200/550, irr.
NSV 14213	L	G8	5.6–6.8 (V)	1191	0.15	0.20	Y, P250(0.02):
V939 Her	Lb	MD	7.24–8.02 (Hp)	1167	0.26	0.53	Y:, irr.
UX Cam	Lb	M6	9.5–10.65 (p)	1029	0.23	0.33	P935(0.04)
V338 Aql	L:	M3	11–12.5 (p)	1018	0.21	0.27	P780(0.02), P4000
TZ Cas	Lc	M2Iab	8.86–10.5 (V)	991	0.29	0.43	P3000 ± 500 (0.05)
SY Peg	Lb	M0	9.6–10.0 (V)	962	0.29	0.34	P1600(0.02):
AZ Dra	Lb	M2	8.0–8.9 (p)	948	0.23	0.28	Y:, irr.
HM Aur	Lb	M	11.3–12.4 (p)	938	0.25	0.37	P280(0.05)
FR Per	Lb	C4,5(R3)	12.2–13.4 (p)	919	0.39	0.50	200/550:, irr.
α Sco	Lc	M1.5Iab–b	0.88–1.16 (V)	906	0.17	0.26	Y:, P7000 (0.07):
AA Cam	Lb	M5(S)	9.0–9.6 (p)	865	0.19	0.29	Y:, P650(0.04)
V396 Cen	Lc:	M4Ia–ab/M6	10.0–10.6 (B)	859	0.23	0.46	Y, P6080 (0.08):

Table continued on following pages

Table 1. Results of time-series analysis of L-type red giant variables, cont.

Star	*Type*	*Spectrum*	*Range*	*N*	*Dm (0)*	*Dm (4000)*	*Comments*
V770 Cas	Lb	M2IIIc	7.45–8.13 (Hp)	844	0.21	0.26	Y, P420(0.06), P3450(0.10):
V370 And	SRb	M7III	6.18–7.19 (Hp)	838	0.20	0.44	P120(0.12)
RY Cyg	Lb	C4,8–6,4(N)	8.5–10.3 (V)	836	0.39	0.43	irr.
V TrA	Lb	C5,5(Nb)	10.0–10.7(p)	774	0.17	0.55	Y, irr.
MS Aql	Lb	M4III	10.6–11.2 (p)	733	0.31	0.39	irr.
GO Peg	Lb	M4	8.6–9.3 (p)	707	0.21	0.21	Y, nsv
α Tau	Lb:	K5III	0.75–0.95 (V)	693	0.12	0.18	Y:, irr.
NSV 13857	Lb	M2	6.3–7.08 (B)	678	0.14	0.16	Y, nsv
TV Cyg	Lb:	M0	10.9–11.4 (p)	653	0.11	0.78	irr.
V4018 Sgr	L:	M4d	9.5–13.6 (p)	639	0.37	1.81	Y:, symbiotic
QZ Cyg	Lb	M3	11.2–12.4 (p)	632	0.27	0.32	Y, irr.
U Ant	Lb	C5,3(Nb)	8.8–9.7 (p)	623	0.27	0.69	Y:, irr.
GL And	Lb	K4	9.6–10.2 (p)	616	0.35	0.35	P4050:, irr.
V807 Aql	Lb:	M6.5	13.0–14.0 (p)	615	0.32	0.54	Y:, P160:
X Lup	L:	—	10.4–12.8 (p)	609	0.50	0.90	M, Y, irr. hline
TY Oph	Lb	C5,5(N)	12.7–15.1	564	0.32	0.43	200/550, P5600(0.04)
CY Cyg	Lb	CS(M2p)	10.0–11.7 (p)	559	0.41	0.53	P13.7(0.05:):
UY And	Lb	C5,4(N3)	7.4–12.3 (V)	553	0.30	0.44	irr.
RU Car	Lb	N3	10.9–12.1 (p)	553	0.32	0.34	P400(0.05)
HO Peg	Lb	M8III	8.3–8.7	552	0.13	0.16	Y:, nsv
RW Vir	Lb	M5III	6.72–7.38 (V)	498	0.22	0.31	Y:, P3900(0.05):
AX Cyg	Lb	C4,5(N6)	7.85–8.86 (V)	506	0.37	0.39	M:, P358(0.04):, nsv:
DR Boo	Lb	K0D	8.06–8.60 (Hp)	465	0.15	0.20	P513(0.01), P2030(0.05)
HU Sge	Lb	M0	7.8–8.8 (p)	462	0.15	0.20	200/550:, P1500(0.02):
AC Dra	Lb	M5IIIab	7.14–7.39 (B)	447	0.13	0.22	P380(0.06) (Y?)
DK Boo	Lb	K5D	8.02–8.77 (Hp)	440	0.18	0.21	nsv
NO Aur	Lc	M2SIab	6.10–6.30 (V)	439	0.19	0.30	P325(0.03):, Y:
NSV 436	Lb	M0	8.4–9.1 (p)	436	0.12	0.20	irr

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Table 1. Results of time-series analysis of L-type red giant variables, cont.

Star	*Type*	*Spectrum*	*Range*	*N*	*Dm (0)*	*Dm (4000)*	*Comments*
FG Boo	Lb	M0D	7.35–8.06 (Hp)	430	0.16	0.40:	P584(0.10)
TT Leo	Lb	M7	10.5–11.7 (V)	429	0.29	0.45	P382(0.05)
V352 Ori	Lb	M7ep	8.5–10.0 (p)	418	0.22	0.28	200/550:, irr.
NSV 4147	L:	—	11.4–12.0 (V)	413	0.18	0.26	200/550, irr.
V1173 Cyg	Lb	M6eaIII	12.3–13.7 (B)	405	0.38	0.55	irr.
V485 Cyg	Lb	M5III	8.9–9.8 (p)	404	0.23	0.40	Y, irr.
UV Cnc	Lb	M4	9.0–10.5 (p)	386	0.27	0.35	P184(0.05), Y
AV Eri	Lb	M2	12.4–13.2 (p)	363	0.3:	1.0:	P120(0.30)
V416 Lac	Lb	M4III	5.05–5.18 (Hp)	354	0.17	0.20	nsv
NQ Cas	Lb	C4,5J(R5)	10.6–11.52 (B)	338	0.22	0.28	irr.
NSV 771	—	M2	11.5–? (p)	337	0.22	0.22	200/550, nsv
XX Cnc	Lb	M4	10.1–11.0 (p)	335	0.36	0.44	irr.
NSV 14284	Lb:	M	11.0–12.0+ (p)	333	0.24	0.44	P125(0.05)
NSV 293	SRS	M4IIIa	5.28–5.50 (V)	327	0.09	0.11	Y, nsv
V2429 Cyg	Lc:	M3	10.4–13.7 (V)	322	0.5	0.5	Y, irr.
SU And	Lc	C6,4(C5II)	8.0–8.5 (V)	310	0.18	0.22	irr.
FR Sct	Z And	M2.5epIab+B	11.6–12.91 (B)	309	0.14	0.20	irr.
LW Cyg	Lb	C5,4(R3)	12.3–14.5+ (B)	299	0.39	0.65	irr.
V727 Sco	Lb:	M1	9.7–10.4 (p)	299	0.18	0.30	200/550, irr.
KP Del	Lb	M5	7.7–8.39 (V)	297	0.19	0.25	Y:, irr.
PV Peg	Lb	—	6.55–7.42 (Hp)	295	0.22	0.30	P120(0.05):
SW Cet	Lb	M7III	9.8–10.9 (p)	294	0.31	0.40	200/550, irr.
EV Peg	Lb	M7	11.5–13.0 (p)	291	0.60	0.65	P235(0.35)
FI Gem	Lb	M6.5	12.8–14.2 (p)	291	0.28	0.45	Y, irr.
FI Vel	L	—	12.6–13.6 (p)	265	0.14	0.50	200/550:, irr.
PX Lyr	L	—	13.0–14.4 (p)	261	0.43	0.65	P400(0.20:), P1450(0.15:)
NSV 2731	L	OB!	11.3–11.7 (p)	253	0.20	0.25	nsv
NSV 13234	L:	K0	9.0–10.2 (V)	249	0.15	0.22	irr. hline

Table 2. Stars recommended by the authors for continued observation, based on the results of this paper, and papers I and II.

Priority Recommendation	*Stars*			
(i) Observe (Higher Priority)	V370 And	V770 Cas	AV Eri	ST Psc
	VW Aql	RX Cru	OP Her	V4018 Sgr
	ψ1 Aur	TZ Cyg	TT Leo	τ4 Ser
	FG Boo	V930 Cyg	EX Ori	CP Tau
	UX Cam	AT Dra	EV Peg	VY UMa
(ii) Observe (Medium Priority)	V338 Aql	UV Cnc	BI Cyg	PX Lyr
	V807 Aql	RU Car	CY Cyg	PV Peg
	HM Aur	TZ Cas	T Lyr	NSV 14284
	UX Cam	AA Cas	X Lyr	
	AA Cam	ST Cep	TU Lyr	
(iii) Observe (Lower Priority)	HM Aur	AX Cyg	PR Per	DY Vul
	NO Aur	BI Cyg	α Sco	NSV 14213
	DR Boo	TY Oph	HU Sge	
	V391 Cas	SY Peg	X TrA	
(iv) Irregular	U Ant	V451 Cas	V2429 Cyg	BL Ori
	SU And	V396 Cen	CT Del	V352 Ori
	UY And	AS Cep	KP Del	ε Peg
	GL And	SW Cet	UW Dra	FR Per
	V Aps	T Cyg	AC Dra:	V727 Sco
	MS Aql	RY Cyg	AZ Dra	FR Sct
	ZZ Cam	SV Cyg	BU Gem	α Tau
	XX Cnc	TV Cyg	FI Gem	V TrA
	W CMa	AX Cyg	GN Her	FI Vel
	RT Car	LW Cyg	V939 Her	RW Vir
	BO Car	QZ Cyg	X Lup	NSV 436
	WW Cas	V485 Cyg	XY Lyr	NSV 4147
	NQ Cas	V1152 Cyg	HK Lyr	NSV 13234
	PY Cas	V1173 Cyg	κ Oph	
(v) Not Significantly Variable	SV Aur	AO Cru	HO Peg	NSV 771
	DK Boo	V449 Cyg	KK Per	NSV 2731
	IZ Cas	WY Gem	PP Per	NSV 13857
	AD Cen	V416 Lac	TX Psc	
	DM Cep	GO Peg	NSV 293	