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Long-Term *VRI* Photometry of Small-Amplitude Red Variables. I. Light Curves and Periods

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ABSTRACT. We report up to 5000 days of *VRI* photometry, from a robotic photometric telescope, of 34 pulsating red giants, namely, TV Psc, EG And, Z Psc, RZ And, 4 Ori, RX Lep, UW Lyn, η Gem, μ Gem, ψ^1 Aur, V523 Mon, V614 Mon, HD 52690, Y Lyn, BC CMi, X Cnc, UX Lyn, RS Cnc, VY UMa, ST UMa, TU CVn, FS Com, SW Vir, 30 Her, α^1 Her, V642 Her, R Lyr, V450 Aql, V1293 Aql, δ Sge, EU Del, V1070 Cyg, W Cyg, and μ Cep, as well as a few variable comparison stars. *V*, *R*, and *I* variations are generally in phase. The length and density of the data enable us to look for variations on timescales ranging from days to years. We use both power-spectrum (Fourier) analysis and autocorrelation analysis, as well as light-curve analysis; these three approaches are complementary. The variations range from regular to irregular, but in most of the stars, we find a period in the range of 20–200 days, which is probably due to low-order radial pulsation. In many of the stars, we also find a period which is an order of magnitude longer. It may be due to rotation, or it may be due to a new kind of convectively induced oscillatory thermal mode, recently proposed by P. Wood.

1. INTRODUCTION

As stars expand and cool to become red giants or asymptotic giant branch (AGB) stars, they become pulsationally unstable. Microvariability sets in at mid-K spectral type (Grenon 1993; Jorissen et al. 1997; Eyer & Grenon 1997; Henry et al. 2000), and variability with a *V* amplitude greater than 0.01 mag sets in at spectral type K9–M0 III (Stebbins & Huffer 1930). By the time the star reaches late-M spectral type, the *V* amplitude is several magnitudes; when it exceeds 2.5 mag, the star is classified as a Mira star (although, as Kiss et al. 1999 have pointed out, there are pulsating red giants such as V Boo, RU Cyg, and Y Per whose amplitudes have decreased from more than 2.5 to less than 2.5 mag within a few years). The small-amplitude red variables (SARVs—a name based on the classification system developed by Eggen 1973a, 1973b, 1975, 1977) are 2 orders of magnitude more numerous than Mira variables. The understanding of these variables has been aided by large-scale photometric surveys, as described in several papers in Szabados & Kurtz (2000).

This is part of a series of papers dealing with the search for (Percy & Fleming 1991; Percy & Shepherd 1992; Percy et al. 1994), period analysis of (Percy et al. 1996), and pulsation modes of (Percy & Parkes 1998) SARVs. For a review, see Percy (1997); the latter paper is part of a special volume of the *Journal of the AAVSO* dealing with Mira stars and related objects.

SARVs tend to pulsate in low-order radial modes—usually the first or second harmonic (Percy & Parkes 1998); this is in general agreement with theoretical expectations (Xiong, Deng, & Cheng 1998). They occasionally switch modes (Cadmus et al. 1991; Percy & Desjardins 1996; Bedding et al. 1998). Kiss et al. (1999) have used visual data to search for *multiperiodicity* in a sample of 93 larger amplitude pulsating red giants: 29 were monoperiodic, 44 were doubly periodic, and 12 were triply periodic. The period ratios were most commonly between 1.8 and 2.0 or between 10 and 12. The former period ratios may be due to the presence of two different radial modes. The nature of the latter period ratios is not known.

2. DATA AND METHODS

Johnson *VRI* data on a selection of SARVs was acquired with the Fairborn-10 (T2) Automatic Photometric Telescope (APT) as described by Henry (1995) and Percy, Bakos, & Henry (2000). The individual observations are available at the Tennessee State University Automated Astronomy Group Web site.[1] The stars chosen were M giant variables whose brightness, position, and amplitude made them accessible to the APT. The data are differential and are corrected for differential extinction and transformed to the Johnson *VRI* system. If the formal error

[1] See http://schwab.tsuniv.edu/t2/sarv1/sarv1.html.

of an observation is greater than 0.02, it is flagged and not used. The comparison and check stars are listed in Table 1. A few comparison or check stars are variable, as noted in Table 1 and as described in the text. Where possible, the variability of these stars has been studied relative to the nonvariable comparison star. Power spectra were determined using the AAVSO program TS (Foster 1995) and/or the program Period98 from the Institute of Astronomy, University of Vienna (Sperl 1998). Autocorrelation analysis was performed as in Percy et al. (1996).

3. RESULTS

The long-term and sample short-term *V* light curves are shown in Figures 1–7, and the results of the light curve and period analysis are summarized in Table 2. The magnitudes and spectral types are taken from the *Bright Star Catalogue* (Hoffleit 1982) or the *Hipparcos* Catalogue (Perryman et al. 1997). In the following section, the results are discussed on a star-by-star basis (LC: light curve; AD: autocorrelation diagram; PS: power spectrum). The results quoted in the *Hipparcos* Catalogue (Perryman et al. 1997) are given: either the period determined from the *Hipparcos* epoch photometry if the star was periodic (P) or the period quoted by Perryman et al. (1997) from the literature if the star was "unsolved" (U). The figures have been chosen so as to illustrate the range of behavior of the stars, including long-term and short-term variability in the light and color curves, simple and complex power spectra, and autocorrelation diagrams. Table 2 summarizes the results. The ranges in *V* and $V-I$, and their ratio, are the total ranges observed. The periods marked with an asterisk are the ones which seem to be most stable and well determined.

TABLE 1
PROGRAM AND COMPARISON STARS

Name	HD	Comparison	Check
TV Psc	2411	46 Psc	52 Psc
EG And	4174	HD 3914	32 And
Z Psc	7561	HR 341	ϕ Psc
RZ Ari	18191	ρ^3 Ari	40 Ari
4 Ori	30959	o^2 Ori	6 Ori
RX Lep	33664	HR 1665	ι Lep
UW Lyn	42973	40 Cam	37 Cam
η Gem	42995	1 Gem	μ Gem (var)
μ Gem	44478	1 Gem	
ψ^1 Aur	44537	47 Aur	ψ^6 Aur
V523 Mon	51725	HR 2599	HR 2624
V614 Mon	52432	HR 2636	HD 52690 (var)
	52690	HR 2636	
Y Lyn	58521	HD 58681	HR 2903
BC CMi	64052	HR 3050	14 CMi
X Cnc	76221	HR 3558	o^2 Cnc
UX Lyn	77443	HR 3580	HR 3612
RS Cnc	78712	τ Cnc	61 Cnc
VY UMa	92839	HR 4176	38 UMa
ST UMa	99592	HD 99606	60 UMa
TU CVn	112264	HR 4919	HR 4843
FS Com	113866	39 Com	35 Com (var)
35 Com	112033	39 Com	
SW Vir	114961	65 Vir	66 Vir
30 g Her	148783	η Her	σ Her
α^1 Her	156014	See text	See text
V642 Her	159354	HR 6542	HR 6594
R Lyr	175865	HD 174621 (var)	16 Lyr
	174621	16 Lyr	
V450 Aql	184313	HD 184853	
V1293 Aql	184201	HD 184853	
δ Sge	187076	α Sge	β Sge
EU Del	196610	HR 7923	HD 196345
V1070 Cyg	203712	HR 8138	HR 8155
W Cyg	205730	71 Cyg	ρ Cyg
μ Cep	206936	12 Cep	ν Cep (var)
ν Cep	207260	12 Cep	

4. NOTES ON INDIVIDUAL STARS

TV Psc (*HR 103, HD 2411, HIP 2219* [*U: literature period 49.1 days*], $V = 5.06$, *M3 III*).—This object shows a period of about 55 days, according to the LC (Fig. 1), AD, and PS, and also a timescale of years; this is also apparent from the LC. Percy et al. (1996) found periods of 53.11 and about 1400 days; these are consistent with Figure 1.

EG And (*HD 4174, HIP 3494* [*U*], $V = 7.18$, *M2e, Z Andromedae type*).—This object shows variations in the LC (Fig. 1) on timescales of 30 and several hundred days. The AD (Fig. 8) clearly shows periods of 28 and 240 days. These are refined in the PS (Fig. 9) to 29 and 242 days. The latter period is half of the orbital period (Oliversen et al. 1985; Fekel et al. 2000: period 482.57 ± 0.53 days), so this is an ellipsoidal variable. Percy et al. (1996) found an uncertain timescale of 200 days or more.

Z Psc (*HD 7561, HIP 5914* [*P: period 147.5 days*], $V = 6.84$, *C5 II*).—This object appears to show at least two periods. There are peaks at 269, 156, and possibly 100 days in the PS, and although the first two are aliases, the AD suggests that there are two or more periods. The first two appear to be the most likely. The cycle shown in Figure 1 is about 150 days long.

RZ Ari (*HR 867, HD 18191, HIP 13654* [*U: literature period 30 days*], $V = 5.91$, *M6 III*).—This object shows a complex light curve with timescales of 20–50 days (Fig. 1); the period is 50–55 days according to the AD and 56.5 (or possibly 49) days according to the PS. There is also a weak period of 25 days in the PS, but it is not apparent in the AD. Percy et al. (1996) found periods of about 56 and about 500 days.

4 Ori (*HR 1556, HD 30959, HIP 22667* [*P: period 30.29 days*], $V = 4.74$, *S3.5/1*.—This object shows a modulated LC with a cycle-count period of 35–40 days (Fig. 1) and possible long-term variations on a timescale of 2–3 years or more. The AD shows a 38 day period clearly and a 600 day timescale very weakly. The PS shows peaks of equal heights at both 36 and 40 days, so we adopt a period of 38 days (although periods of both 36 and 40 days could both be present). There is a peak

TABLE 2
CHARACTERISTICS OF THE RED VARIABLES

Name	HD	Spectral Type	ΔV	$\Delta(V-I)/\Delta V$	Period(s) (days)
TV Psc	2411	M3 III	0.5	0.85	55*, 570–1400
EG And	4174	M2e	0.3	0.74	29*, 242*
Z Psc	7561	C5 II	0.8	0.60	156:, 269:
RZ Ari	18191	M6 III	0.4	…	56.5*, shorter
4 Ori	30959	S3.5/1	0.3	0.76	38*, 650+, 5000
RX Lep	33664	M6 III	0.5	0.69	80, long
UW Lyn	42973	M3 IIIab	0.15	0.93	35, 50
η Gem	42995	M3 III	0.3	0.76	234*, shorter?
μ Gem	44478	M3 III	0.1	…	27*, long
ψ^1 Aur	44537	K5–M0 Iab–Ib	0.7	0.83	150–200:, 2000
V523 Mon	51725	Mb	0.2	…	33.8* (or 45; complex)
V614 Mon	52432	C4,4	0.4	0.83	80.7*
Y Lyn	58521	M5 Ib–II	0.8	0.76	110*, 1400*
BC CMi	64052	M4 III	0.5	0.75	20 and 30?, long
X Cnc	76221	C6 II	0.6	0.52	200, 375
UX Lyn	77443	M6 III	0.4	0.88	20:, 37.3*, 420
RS Cnc	78712	M6 IIIase	1.0	0.86	50–150:, 2000
VY UMa	92839	C5 II	0.5	0.55	125, 190:
ST UMa	99592	M4/5 III	0.7	0.80	50, 81*, 625*
TU CVn	112264	M5 III	0.35	0.83	44.5*, 230:
FS Com	113866	M5 III	0.35	0.86	55.1*, shorter, 600–750:
SW Vir	114961	M7 III	1.8	0.67	153.8*, long
30 Her	148783	M6 III	0.6	0.82	93*, 833*
α^1 Her	156014	M5 Ib–II	1.0	0.63	128, long
V642 Her	159354	M4 III	0.2	…	25.6*, 500–1500:
R Lyr	175865	M5 III	0.6	0.75	46 and/or 64
V450 Aql	184313	M5/5.5 III	…	0.78	65*
V1293 Aql	184201	M5 III	0.6	…	70:, 270:
δ Sge	187076	M2 II+A0 V	0.16	0.82	25, 47.4*
EU Del	196610	M6 III Fe-1	0.7	0.78	62.3*, long
V1070 Cyg	203712	M7 III	0.5	0.70	60, 50±, complex
W Cyg	205730	M5 IIIae	1.0	0.80	130.4*, complex
μ Cep	206936	M2 Iae	0.8	0.93	840*

NOTE.—The periods marked with an asterisk are the ones which seem to be most stable and well determined.

at 657 days, but there are other peaks at low frequencies which are almost as strong.

RX Lep (*HR 1693, HD 33664, HIP 24169* [*U: literature period 60 days*], $V = 5.68$, *M6 III*).—This object shows a complex LC with a timescale of 70–80 days (Fig. 2); the AC shows some evidence for a period of 75 ± 25 days and several timescales of 200–900 days; the PS is also complex, with no peaks standing out. Figure 2 suggests that there is also variability on a timescale of thousands of days.

UW Lyn (*HR 2215, HD 42973, HIP 29919* [*U*], $V = 4.98$, *M3 IIIab*).—This object shows very complex behavior. The PS of the whole data set shows periods of 37.6 and 49.5 days. Individual seasons show periods of 35–40 and 47–50 days. The AD also suggests two or more periods in the range of 30–50 days. The light curve is complex (Fig. 2); the cycle-count period is about 30–40 days. There is also a long-term variation of 0.05 on a timescale of 1500 days. Fig. 10 shows the light and color curves and the correspondence between them.

η Gem (*HR 2216, HD 42995, HIP 29655* [*P: period 233 days*], $V = 3.28$, *M3 III*).—This object shows a period of 200 days in the LC. The AD is very simple and shows a period of 240 days, which is refined in the PS to 234 days. There is no evidence for long-term variability, but Figure 2 suggests that there may be very low level variability on a timescale of 20 days. Percy et al. (1996) found a period of 238.8 days.

One of the comparison stars is slightly variable, and we believe this to be the check star μ Gem, which is an M giant. The comparison star is a G7 giant which is not variable, according to the *Hipparcos* Catalogue.

μ Gem (*HR 2286, HD 44478, HIP 30343* [*U*], $V = 2.88$, *M3 III*).—This object shows variability with a period of 27 days, according to the LC (Fig. 2), AD, and PS; there are also variations in amplitude and mean magnitude on a timescale of 2000 days.

ψ^1 Aur (*HR 2289, HD 44537, HIP 30520* [*U*], $V = 4.91$, *K5–M0 Iab–Ib*).—This object shows conspicuous long-term

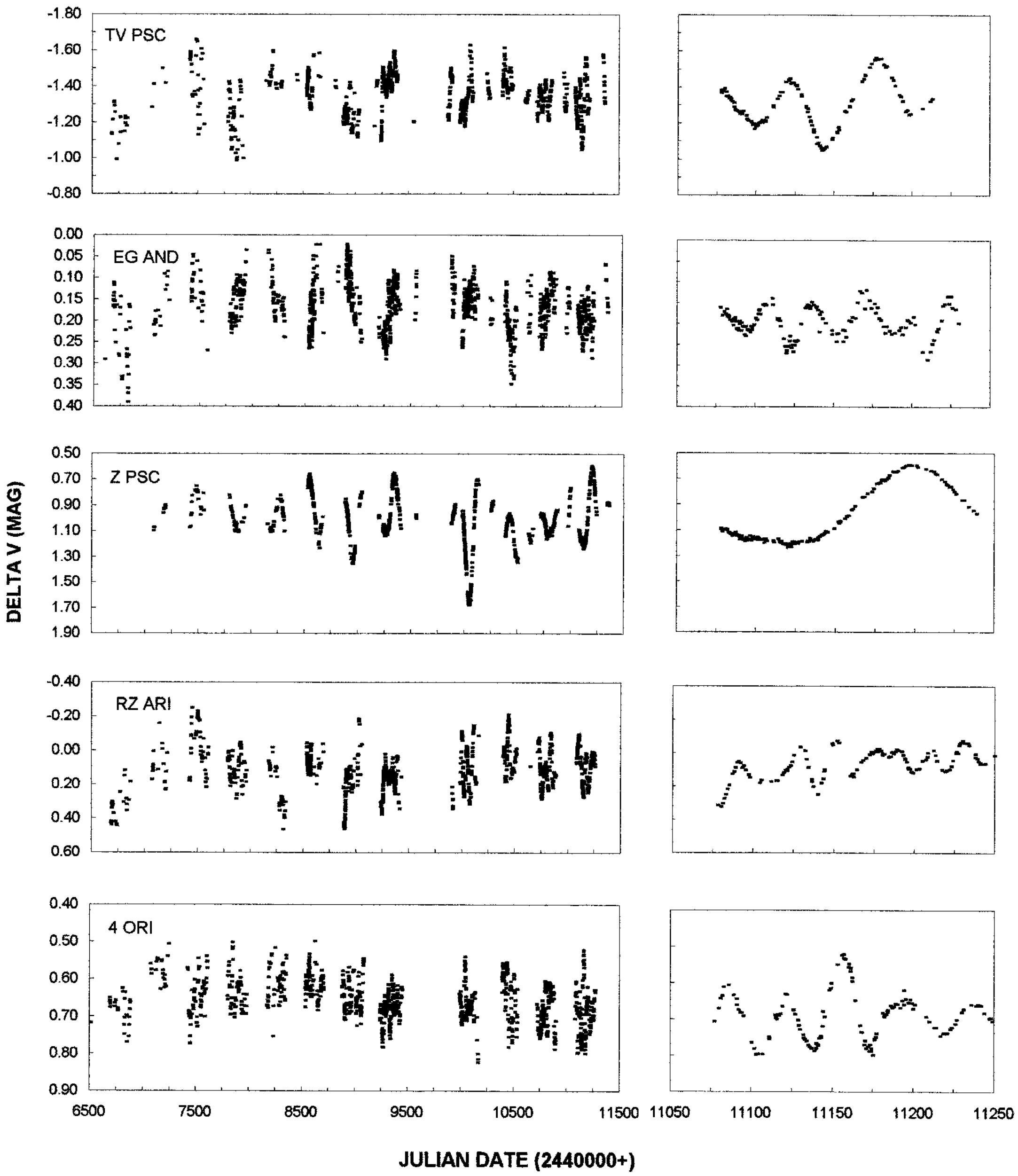

FIG. 1.—Differential *V* light curves of TV Psc, EG And, Z Psc, RZ Ari, and 4 Ori, relative to the comparison stars listed in Table 1.

variations on a timescale of 2000 days, but there is evidence, in both the light curve (Fig. 2) and the AD, for variability on a timescale of about 150–200 days also. There are several weak peaks in the PS in this range, but none of them stands out.

V523 Mon (*HD 51725, HIP 33530* [*U: literature period 45 days*], $V = 6.96$, *Mb*).—This object shows a main peak at 33.8 days in the PS, with probable alias periods of 26 and 45 days. The AD and the LC suggest that the 33.8 day period is the correct one, although the *Hipparcos* reference supports the 45 day period. Indeed, the LC (Fig. 3) suggests that two periods may be present. There are no obvious long-term variations, but there is a suggestion that the amplitude of the 33.8 day variation is itself variable, with minima at JD 2,447,000 and 2,450,000 (Fig. 3).

V614 Mon (*HD 52432, HIP 33794* [*U: literature period 60 days*], $V = 7.01$, *C4,4*).—This object shows a clear, dominant period of 80.7 days in the LC (Fig. 3), PS, and AD. All three, however, suggest that there may be a secondary period of comparable length. There are no significant long-term variations. Wasatonic (1991) found a period of 90 ± 20 days; Percy et al. (1996) found a period of 80 days, plus long-term variability.

The magnitude difference between the comparison star

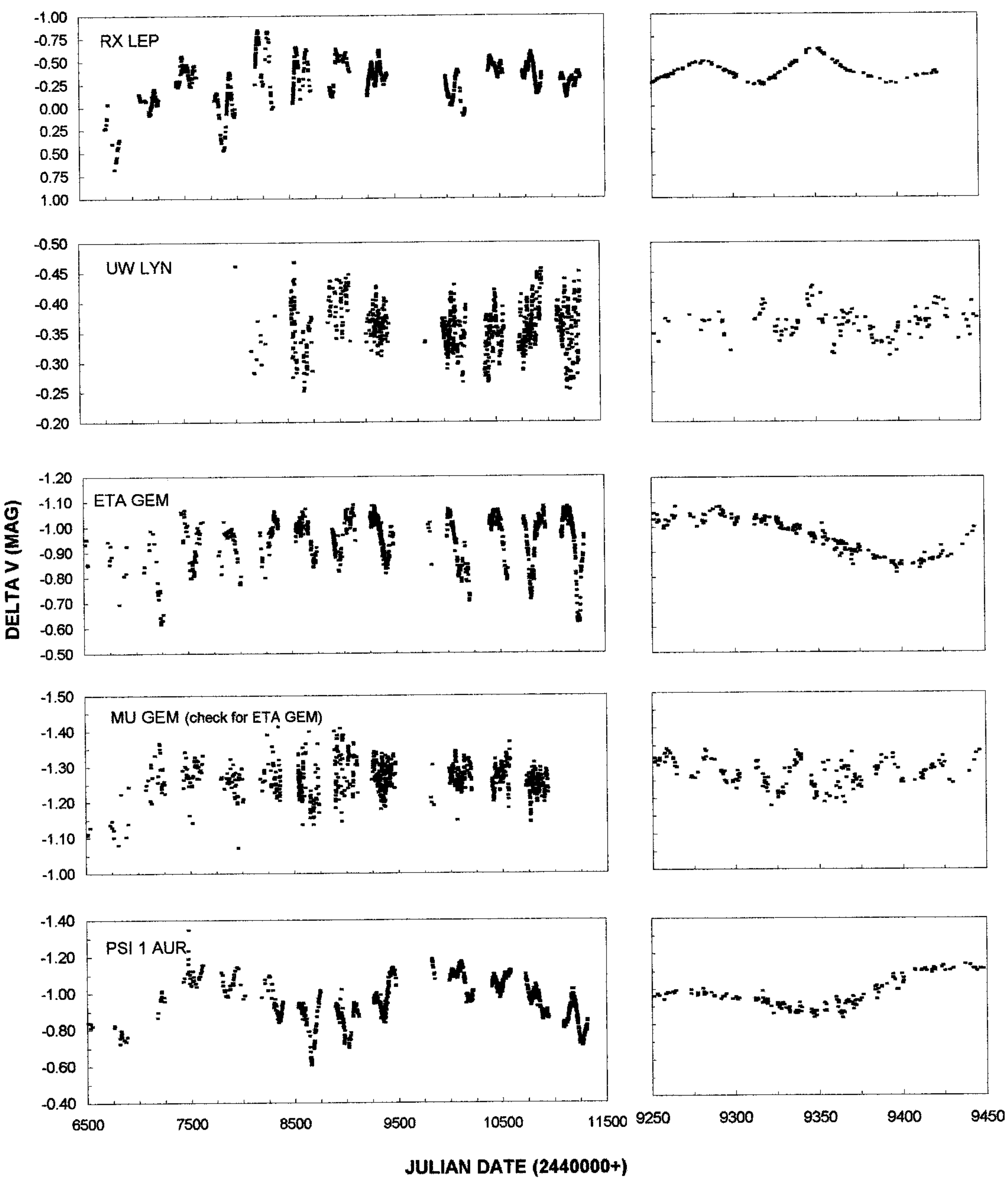

FIG. 2.—Differential *V* light curves of RX Lep, UW Lyn, η Gem, μ Gem (check star for η Gem), and ψ^1 Aur, relative to the comparison stars listed in Table 1.

HR 2636 (K0) and the check star HD 52690 (an M supergiant) is slightly variable; we assume that it is the check star that is slightly variable.

HD 52690 (*HIP 33891* [*U*], *V* = 6.58, *M1 Ib comp SB*).—The LC shows evidence for variability on timescales of 30–35 days and also about 2000 days (Fig. 3). There are peaks in the PS at periods of 39 and 1450 days. The AD suggests timescales of 900 days and longer; there is also a weak minimum at about 30 days, but there is no evidence for the 39 day timescale.

Y Lyn (*HD 58521, HIP 36288* [*U: literature period 110 days*], *V* = 6.98, *M5 Ib–II*).—This object shows remarkable behavior: there is a clear period of 110 days in the AD and LC and a strong period of 1400 days in the PS, AD, and LC (Fig. 3).

BC CMi (*HR 3061, HD 64052, HIP 38406* [*P: period 34.13 days*], *V* = 6.31, *M4 III*).—This object shows an LC with a cycle-count period of 25 days, irregularity which suggests the presence of an additional short period and very slow irregular

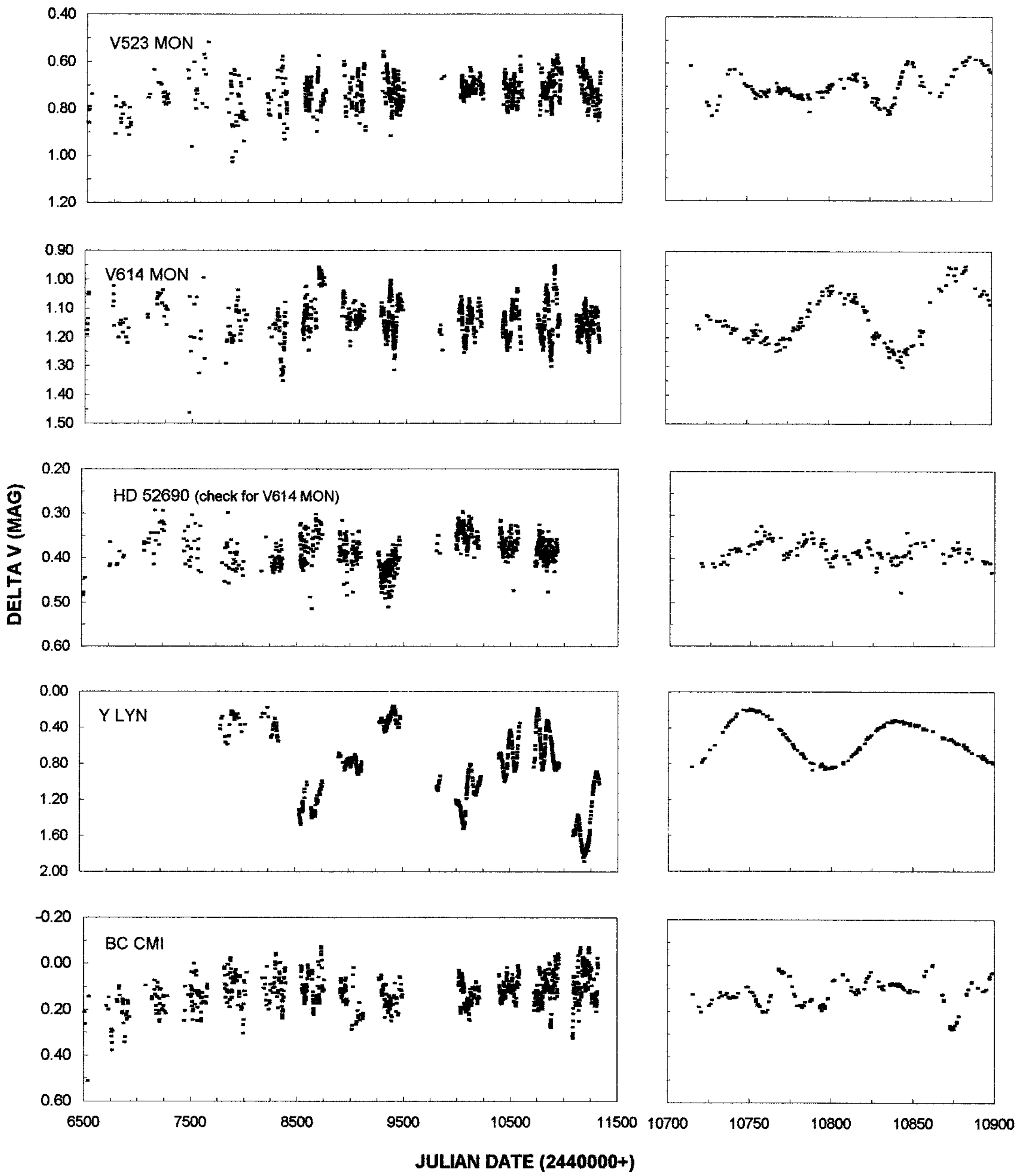

FIG. 3.—Differential *V* light curves of V523 Mon, V614 Mon, HD 52690 (check star for V614 Mon), Y Lyn, and BC CMi, relative to the comparison stars listed in Table 1.

variations (Fig. 3). The AD is slightly complicated but shows periods of 30 and (weakly) 300 days; it is flat at longer periods. The PS is complex: there are peaks at 20 and 30 days, but subsets of the data give periods of 20 and 25 days.

X Cnc (*HR 3541, HD 76221, HIP 43811* [*U: literature period 195 days*], $V = 6.64$, *C6 II*).—This object shows peaks of 192 and 373 days in the PS. These are alias periods, but the AD suggests that there may be two real periods; it shows deep minima at 375 days and twice this value and shallower minima at 200 and 600 days. The LC shows a strong cycle-count period of about 200 days (Fig. 4) but also with a suggestion of a second period. Kiss et al. (1999) found periods of 193, 350, and 1870 days from visual observations.

UX Lyn (*HD 77443, HIP 44481* [*U*], $V = 6.60$, *M6 III*).—This object shows a clear 37.3 day period in both the AD and the PS; the period appears to be very regular—it extends over more than 25 cycles in the AD. There is also some evidence for an approximately 420 day period in the AD. The LC is more complex (Fig. 4); it suggests that there is also variability on a timescale of about 20 days.

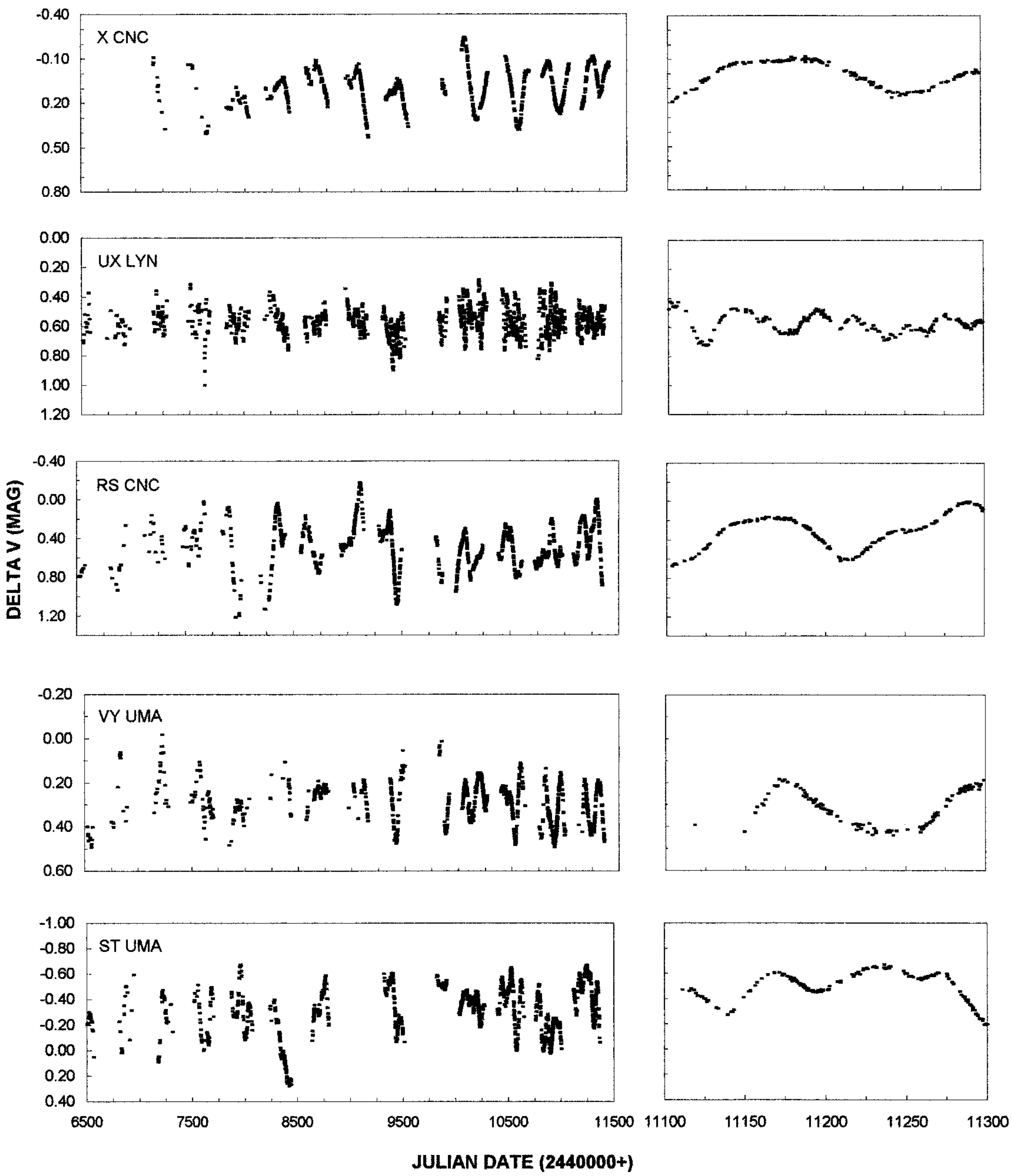

FIG. 4.—Differential *V* light curves of X Cnc, UX Lyn, RS Cnc, VY UMa, and ST UMa, relative to the comparison stars listed in Table 1.

RS Cnc (*HR 3639, HD 78712, HIP 45058* [*U: literature period 120 days*], $V = 5.95$, *M6e Ib–II*).—This object shows complex variability on a variety of timescales, ranging from 50–100 days, to 200 days, as shown by the LC (Fig. 4). The AD supports the latter timescale; the PS shows some peaks at periods of 145 days and greater. Percy et al. (1996) found a period of 228 days and variability on a long timescale.

VY UMa (*HR 4195, HD 92839, HIP 52577* [*U*], $V = 6.00$, *C5 II*).—This object shows complex behavior. There are peaks at 124.7 and 188 days in the PS. These are alias periods, but the AD (which does not suffer from aliasing) also suggests two periods of this order, so it is possible that there are two real periods. The long-term LC is also very complex and may reflect the superposition of two or more periods. The segment shown in Figure 4 has a cycle length of 125 days. Percy et al. (1996) found an uncertain timescale of about 200 days.

ST UMa (*HD 99592, HIP 55936* [*U: literature period 110 days*], $V = 6.0$, *M4/5 III*).—The light curve shows variations on a timescale of 50–100 days (Fig. 4). The AD gives a period of 90 days and the PS of 81 days, which is in reasonable

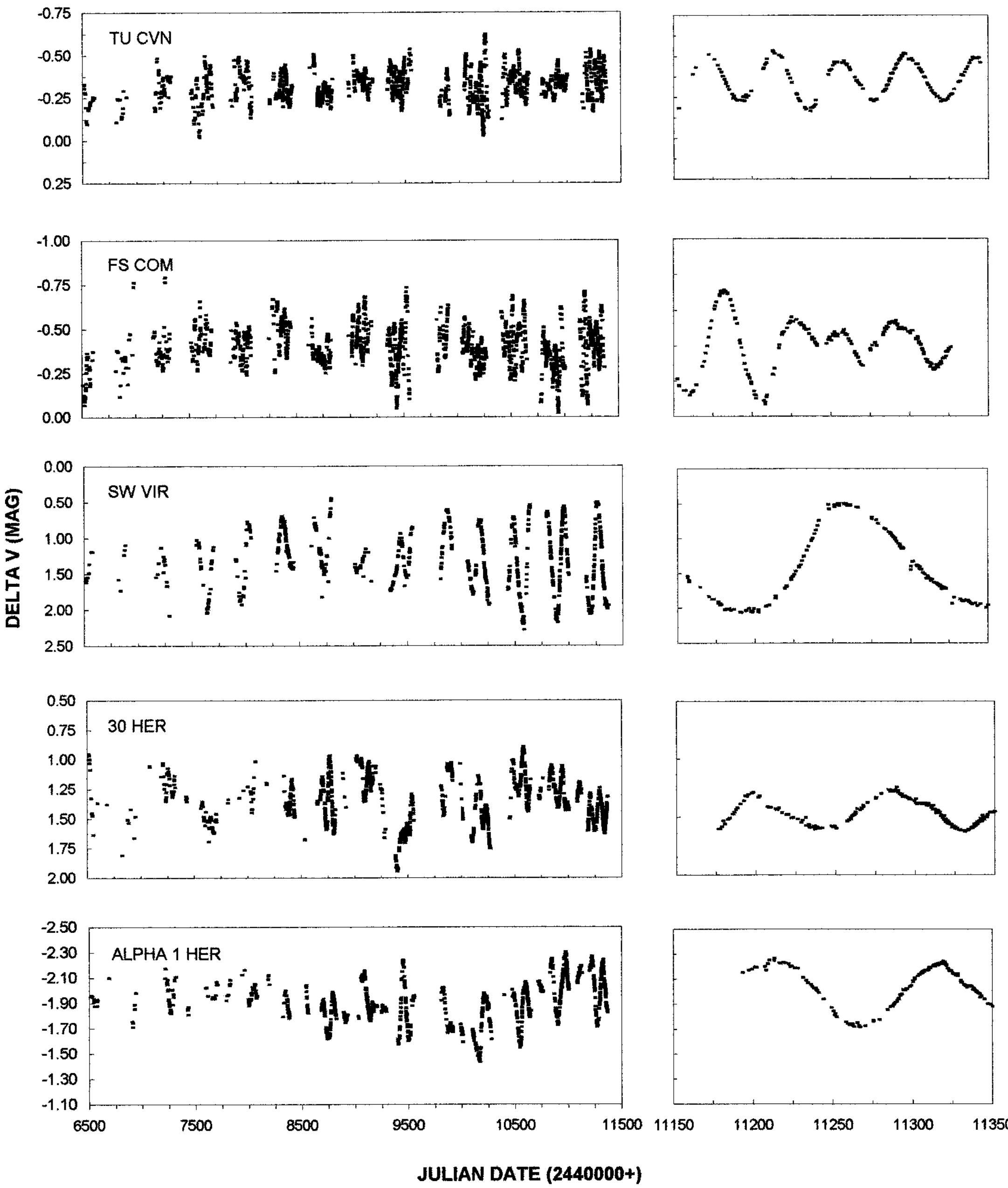

FIG. 5.—Differential *V* light curves of TU CVn, FS Com, SW Vir, 30 Her, and α^1 Her, relative to the comparison stars listed in Table 1.

agreement. Both also show evidence for a period of 625 days. Kiss et al. (1999) found periods of 615 and 5300 days from visual observations.

TU CVn (*HR 4909, HD 112264, HIP 63024* [*U: literature period 50 days*], $V = 5.84$, *M5 III*).—The LC shows clear variability on a timescale of 45 days (Fig. 5). The very impressive AD (Fig. 11) shows 22 minima in 980 days, for a period of 44.5 days; the PS gives 44.2 days (a peak at 39.5 days is probably an alias). There is also some evidence in the AD and PS for a timescale of 230 days.

FS Com (*HR 4949, HD 113866, HIP 63950* [*U: literature period 58 days*], $V = 5.60$, *M5 III*).—The AD gives a period of 50 ± 10 days; the PS gives 55.1 days; there is some evidence for a longer timescale of 600–750 days. The LC (Fig. 5) strongly suggests the presence of an additional shorter period. Percy et al. (1996) found a period of 55.51 days, plus longer term variability.

Either the comparison star 39 Com or the check star 35 Com may be slightly variable. Both are considered nonvariable by the *Hipparcos* Catalogue, with the ranges being 0.03 and 0.02,

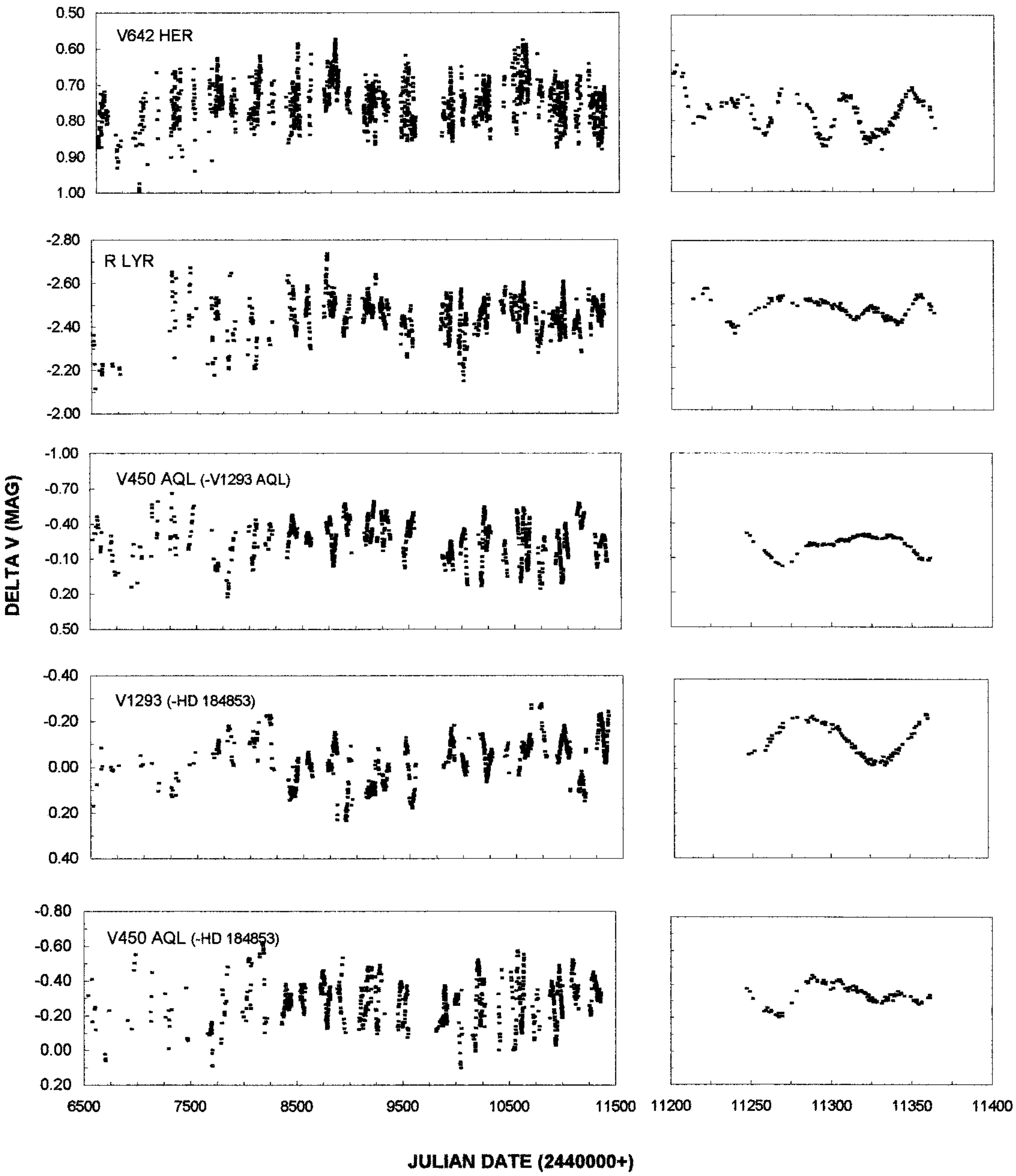

FIG. 6.—Differential *V* light curves of V642 Her, R Lyr, V450 Aql, and V1293 Aql, relative to the comparison stars listed in Table 1. See text for a discussion of the last two stars; in the fourth panel, V1293 is V1293 Aql, relative to the check star.

respectively. The range of the (comparison−check) magnitude difference is only a few hundredths of a magnitude, and we cannot determine which star (if either) is variable.

35 Com (*HR 4894, HD 112033, HIP 62886, V* = 4.90*, G8 III+F6 V*) (*assuming this to be the variable*).—This object has a range of only 0.03 mag. The nature of the (possible) variability is not clear; according to the *Bright Star Catalogue,* 35 Com is a visual binary with $a = 1\farcs42$ and a period of several centuries, and according to Eaton (1990), the projected rotational velocity is less than 5 km s^{-1}, so it does not seem to be an RS CVn type star. The timescale of variability, if any, seems to be 190 days or more.

SW Vir (*HD 114961, HIP 64569* [*P: period 153.6 days*], *V* = 6.85*, M7 III*).—The LC shows variations on a timescale of 150 days (Fig. 5), the AC gives 150 days, and the PS gives 153.8 days. Kiss et al. (1999) found periods of 154, 164, and 1700 days from visual observations. The LC (Fig. 5) also shows weak evidence for the 1700 day period.

30 g Her (*HR 6146, HD 148783, HIP 80704* [*U: literature period 89.2 days*], *V* = 5.04*, M6 III*).—This object shows clear

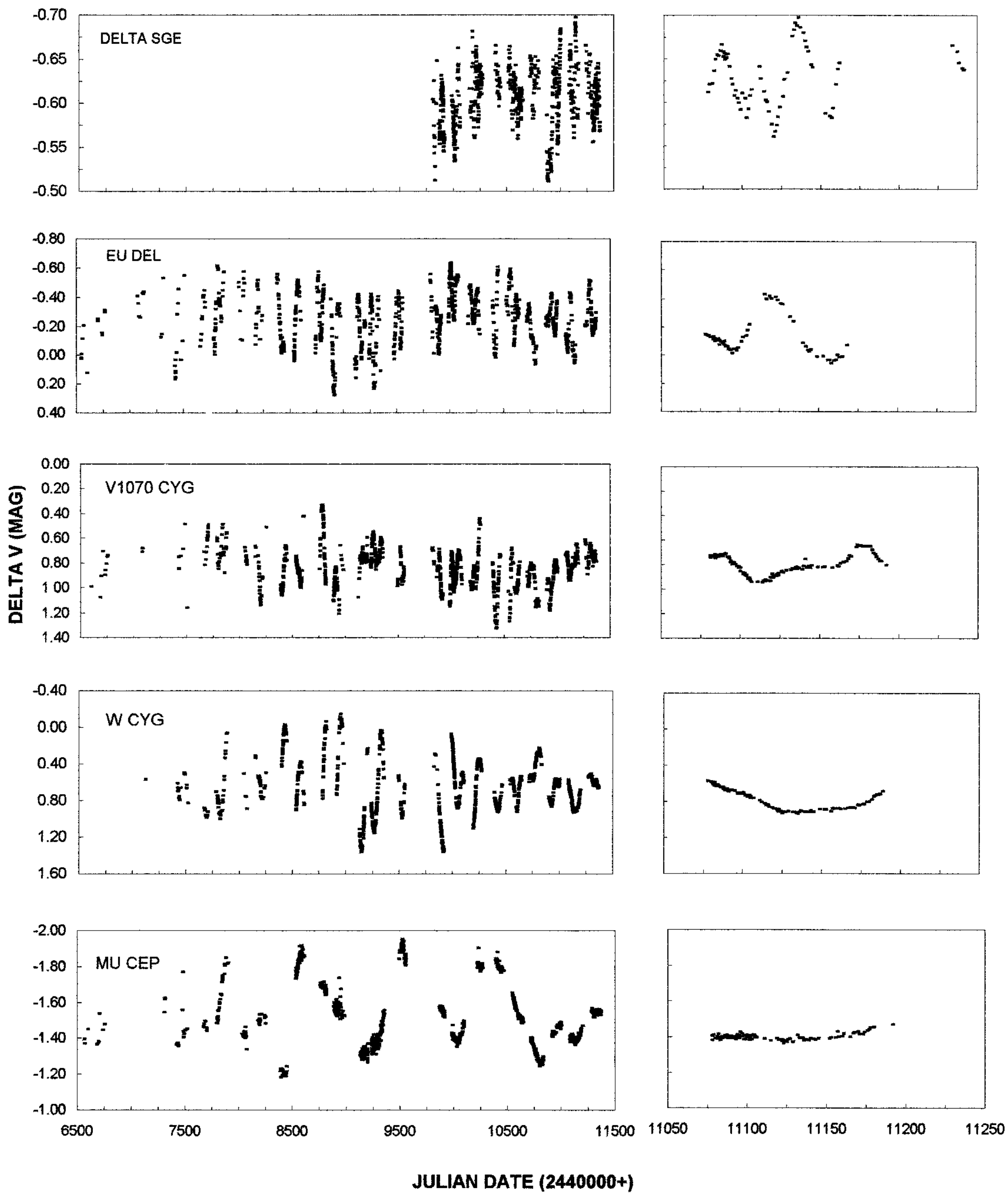

FIG. 7.—Differential *V* light curves of δ Sge, EU Del, V1070 Cyg, W Cyg, and μ Cep, relative to the comparison stars listed in Table 1.

variations in the LC on two timescales—100 days and 1000 days (Fig. 5). The AD (Fig. 12) gives timescales of 60–100 days and 900 days, and these are refined in the PS to either 83 or 93 days and 833 days. The AD favors the 93 day short period. Kiss et al. (1999) found periods of 90 and 887 days from visual observations. F. C. Fekel (2001, private communication), in a new study using infrared radial velocities, finds a radial velocity period of 844 days, which is very close to one of our periods.

64 α^1 Her (*HR 6406, HD 156014, HIP 84345* [*U*], *V* = 3.48, *M5 Ib–II*).—This object was observed relative to the following comparison (CO) and check (CK) stars: JD 2,446,510–2,448,375: HR 6337 (CO) and α^2 Her (CK); JD 2,448,378–2,448,441: HR 6342 (CO) and HR 6443 (CK); JD 2,448,530 onward: HR 6337 (CO) and HR 6443 (CK). The star shows clear variations in the LC on timescales of 80–140 days and also 1000–3000 days (Fig. 5). The AD is very complicated; there are minima at 130, 180, and 240 days and longer

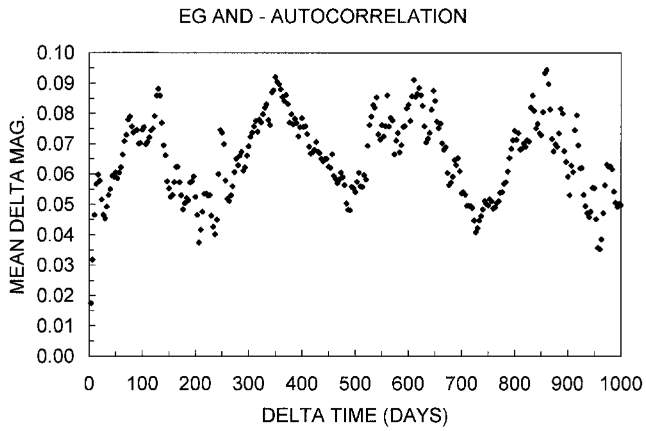

FIG. 8.—Autocorrelation diagram for EG And, showing minima at multiples of both 28 and 240 days. This star has conspicuous variations on both timescales.

periods. The highest peak in the PS is at 128 days; there is also a peak at 200 days which is an alias of this. Our suspicion is that there is another short period in addition to 128 days and also some irregular long-term variability.

V642 Her (*HR 6543, HD 159354, HIP 85934* [*U: literature period 12 days*], $V = 6.48$, *M4 III*).—This object shows a clear period of 25.6 days in the LC (Fig. 6), PS, and AD. The 25 day variations are somewhat irregular, and there are also long-term variations on a timescale of 500–1500 days (Fig. 6).

R Lyr (*HR 7157, HD 175865, HIP 92862* (*U: literature period 46 days*), $V = 4.04$, *M5 III*).—The LC (Fig. 6) shows complex variability on timescales as short as 40 days; the PS is complex and shows peaks at 46 and 64 days, among others. Percy et al. (1996) found a period of 53.41 days, plus longer term variability. Figure 13 shows the correspondence between the $V-I$ color variations and the V light variations.

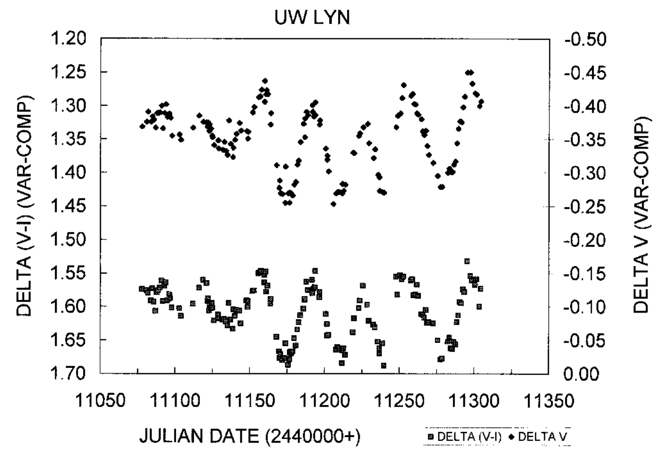

FIG. 10.—Light and color curves for UW Lyn, showing the correspondence between the $V-I$ color curve and the V light curve, and also showing the cycle-count period of 34 days.

There is evidence for long-term variability (0.05) in the magnitude difference between the comparison star 16 Lyr and the check star HD 174621. Both stars are nonvariable according to the *Hipparcos* Catalogue, the ranges being 0.02 and 0.03, respectively.

HD 174621 (*HIP 92352*, $V = 6.54$, *G5*) (*assuming it to be variable*).—This object shows a total range of 0.16 in the V light curve (but see above); some of this may be instrumental scatter. The timescale, if any, is 80 days or more. The star may be an active rotating variable.

V450 Aql (*HD 184313, HIP 96204* [*U: literature period 64.2 days*], $V = 6.30$, *M5/5.5 III*).—The LC shows cycles of 50–80 days in length (Fig. 6, *bottom panel*); the AD shows a clear period at 65 days, although this is not particularly evident in

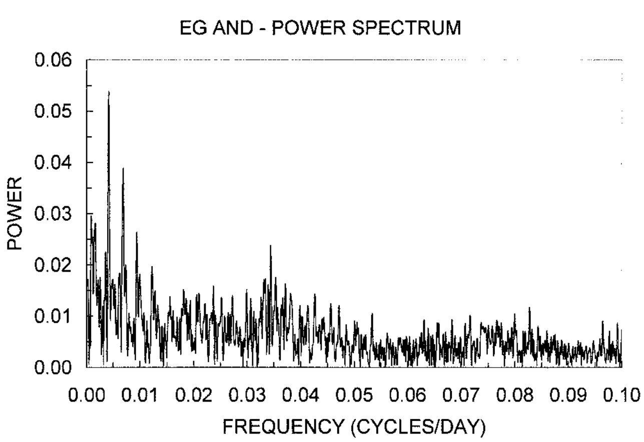

FIG. 9.—Power spectrum for EG And, showing peaks corresponding to periods of 29 and 242 days. This star shows conspicuous variations on both timescales.

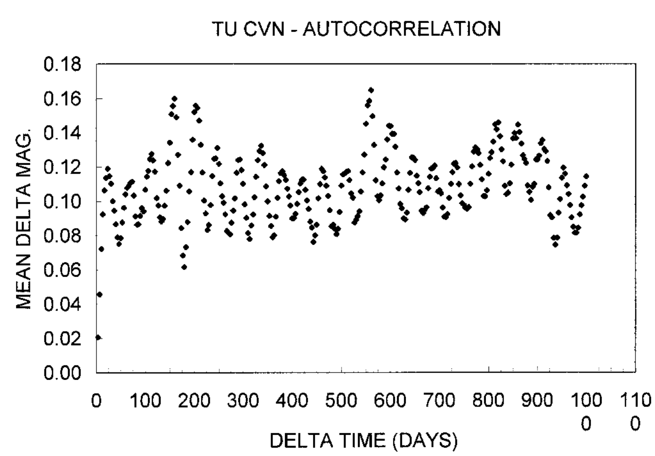

FIG. 11.—Autocorrelation diagram for TU CVn, showing 22 minima in 980 days, or a strict period of 44.5 days.

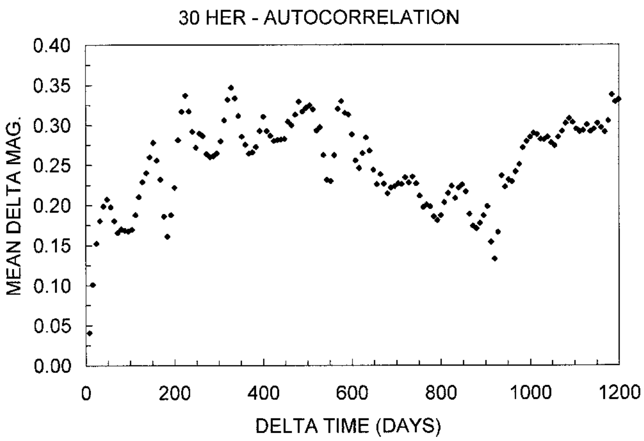

FIG. 12.—Autocorrelation diagram for 30 g Her, showing minima at multiples of 100 days, and also at 1000 days. This star shows conspicuous variations on both timescales.

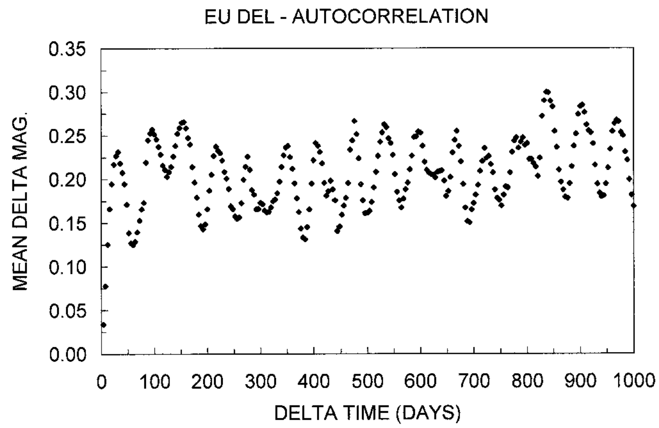

FIG. 14.—Autocorrelation diagram for EU Del, showing minima at multiples of 63 days, indicating a strict underlying periodicity in this star.

the PS. The results are therefore in satisfactory agreement with the literature period.

The comparison star for V450 Aql is itself a named variable star V1293 Aql, so we have analyzed the differences (V450 Aql−check) and (V1293 Aql−check). All three LCs are shown in Figure 6.

V1293 Aql (*HD 184201, HIP 96159* [*U*], *V* = 6.61, *M5 III*).—The LC shows complex cycles on timescales of 75 days or more (Fig. 6); the AD and PS are also complex and suggest periods of 70 and 270 days.

δ Sge (*HR 7536, HD 187076, HIP 97365* [*U*], *V* = 3.82, *M2 II+A0 V*).—The LC shows variations on a timescale of 25 and about 1000 days (Fig. 7); the AD gives a period of 50 ± 10 days, and the PS gives 47.4 days.

EU Del (*HR 7886, HD 196610, HIP 101810* [*P: period 62.27 days*], *V* = 6.25, *M6 III Fe-1*).—This object is almost a "prototype" of small-amplitude red variables, except that its variability is exceptionally simple. The LC shows 60 day cycles with variable amplitude (Fig. 7). The AD (Fig. 14) is extremely "clean" and shows a period of 61.5 days, which is refined in the PS (Fig. 15) to 62.3 days. There is weak evidence in the AD for a period of 345 days and in the LC for a timescale of 2000 days. Percy et al. (1996) found a period of 62.74 days. Kiss et al. (1999) found a single period of 62 days from visual observations.

V1070 Cyg (*HD 203712, HIP 105562* [*U: literature period 73.5 days*], *V* = 7.12, *M7 III*).—This object shows periods of 43, 64, and 100 days in the PS; the AD also hints at two or more periods—perhaps 50 and 80 days. The LC is also very complex, with some cycles 50 days long and others longer (Fig. 7).

W Cyg (*HR 8262, HD 205730, HIP 106642* [*P: period 132.0 days*], *V* = 5.53, *M5 IIIae*).—This object shows a clear period

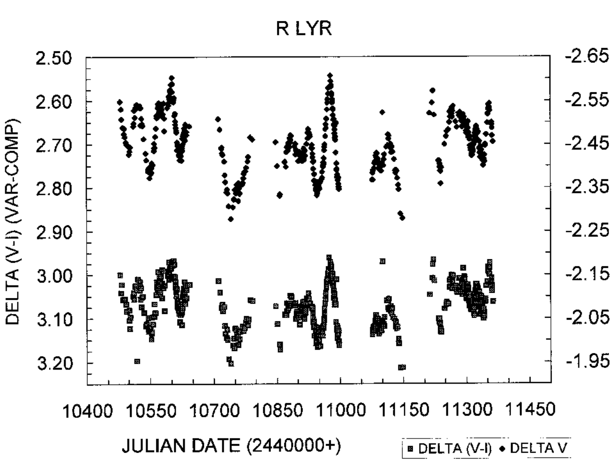

FIG. 13.—Light and color curves for R Lyr, showing the correspondence between the $V-I$ color curve and the V light curve, and also showing the complex variations.

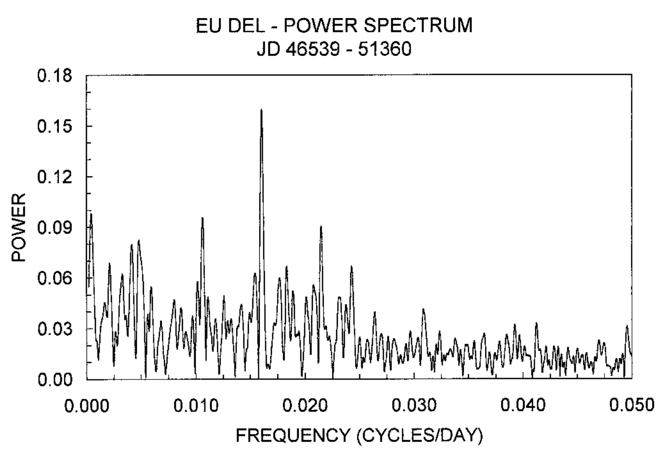

FIG. 15.—Power spectrum for EU Del, showing a conspicuous peak corresponding to a period of 63 days. The alias structure is complex; the two secondary peaks are separated by 2 cycles yr^{-1} from the main peak.

of 130.4 days in the PS and the AD. The LC suggests more complex behavior (Fig. 7), with possible long-term variability as well. Percy et al. (1996) found periods of about 120 and 260 days. Kiss et al. (1999) found periods of 130 and 240 days from visual observations. The extensive literature on this star suggests that it switches between these two different periods.

μ Cep (*HR 8316, HD 206936, HIP 107259* [*U: literature period 730 days*], $V = 4.08$, *M2 Iae*).—The LC shows a timescale of 1000 days (Fig. 7), the AD gives 800–900 days, and the PS gives 840 days.

Either the comparison star 12 Cep or the check star *ν* Cep may be slightly variable. Their spectral types are M1 III and A2 Ia, respectively, both types being prone to variability. Their ranges are 0.03 and 0.05, respectively, according to the *Hipparcos* Catalogue.

10 ν Cep (*HR 8334, HD 207260*, $V = 4.29$, *A2 Ia*) *or 12 Cep* (*HR 8339, HD 207528*, $V = 5.52$, *M1 IIIb*).—The range is only 0.035 mag; the AD shows some evidence for a timescale of 170 days; the PS shows many peaks at periods of 90 and 190 days and longer. This is typical of luminous supergiant variables of A type and not unreasonable for a pulsating red giant.

5. DISCUSSION

We have significantly increased the number of SARVs in which short-term and/or long-term variability has been studied. Unlike other studies (Percy et al. 1996, for instance), we have obtained multicolor photometry. Our results support and extend the results of earlier studies, namely, the following:

1. Red giants, starting at M0 III, are variable with significant amplitude (late K giants are microvariable [Henry et al. 2000] and appear to be related to the M giant variables). The amplitude of variability definitely tends to be greater in cooler giants, although the relationship is not exact. Since our sample is not a random one, it is difficult to draw general conclusions of this sort.

2. Most red giant variables have an underlying periodicity of 20–200 days, although the variability is usually semiregular at best. The periodicity is usually due to radial pulsation (Cummings 1999); the modes have been identified in some stars (Percy & Parkes 1998; Henry et al. 2000).

3. Several of the stars in this study appear to have two periods with a ratio of 2.0 or less, in agreement with the results of Kiss et al. (1999) on stars with larger amplitudes.

4. Many red giant variables have a second periodicity or timescale an order of magnitude longer than the radial pulsation period (see also Kiss et al. 1999), and several of these have been found or confirmed in this study. This longer period may be due to a convectively induced oscillatory thermal (COT) mode (Wood 2000) or due to rotation (Cummings 1999). According to Wood (2000), the COT modes are highly damped, but this result may depend on the treatment of convection. Our results may therefore contribute to a better understanding of convection.

5. The $V-I$ color variations closely follow the V light variations but are slightly smaller in magnitude.

We are now in the process of carrying out further studies of these and related stars, using the results of this and other studies, as follows:

1. We are using both autocorrelation and power spectrum analysis to study the periodicity of the very small amplitude K5–M0 III variables discovered by Henry et al. (2000). How regular are these variables? What mode(s) are present? Do they show long-term variability as the SARVs do? (We note that Koen & Laney 2000 have found several pulsating red giants with periods less than 10 days, using *Hipparcos* data.)

2. We are using wavelet analysis as a tool for studying the amplitude variability and the irregularity of the red giant variables, as Bedding et al. (1998) and Kiss et al. (1999) have successfully done for some larger amplitude pulsating red giants. Is the irregularity due to the presence of secondary periods? Is the amplitude of the primary period intrinsically variable? Is there evidence for mode switching in any of these stars?

3. Using the larger sample of SARVs for which primary periods are known, we will determine the pulsation modes in as many SARVs as possible, using the improved temperature, bolometric correction, and luminosity data now available. What modes are present? Do the modes vary systematically with any physical property of the star—temperature, for instance?

4. Using the larger sample of SARVs for which long periods have also been determined, we will look for correlations between the ratio of the long and the short periods of these variables and any other physical properties of the stars; this may help to differentiate between the two possible explanations for the long period (Cummings 1999; Wood 2000). Ultimately, the most important function of these variables may be to shed light on the convective processes which dominate the outer layers of these stars.

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