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Photometry of 20 eclipsing and ellipsoidal binary systems

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Abstract

A total of almost 2000 V observations of 20 eclipsing and ellipsoidal bright binary stars was collected between 1991 and 2001 for the purpose of determining more recent epoch ephemerides for the light curves than are available in the literature. The original purpose was to provide the Sydney University Stellar Interferometer (SUSI) with orbital periods and particularly the accurate times of minimum separation (light curve minima), so that the SUSI observations need not be used to determine them.

This paper provides the periods, the times of primary minima and the phases of secondary minima for the 20 stars at an epoch as near as possible to the year 2000. No attempt has been made in this report to determine other parameters such as apsidal motion or stellar radii.

Since the program was started in 1991, data for these stars taken in the period from late 1989 to early 1993 has also been available from the Hipparcos satellite; the light curves shown here include both sets of observations.

1 Introduction

Between 1991 and 2001 many observations were obtained of bright eclipsing or ellipsoidal binary stars which may also be observed with the Sydney University Stellar Interferometer, SUSI, at its latitude of 30°S. The separations of these spectroscopic binaries are easily resolved by SUSI so that their observed position angles and angular separations will in principle enable their orbits to be obtained by methods similar to those used for visual binary observations. In particular, the inclinations i of their orbits can be determined, so that where there are good orbital velocity data, the dimensions of their orbits and the individual masses of one or both of the components of each system will also be obtained. In addition, most of the the components' diameters are also expected to be resolved, so that the combination of angular diameters and angular orbital separations with the linear orbital dimensions will enable the distance of the systems to be determined essentially geometrically. In turn, this also enables the linear dimensions of each star to be determined.

The purpose of the present program was to obtain photometry to enable some parameters to be fixed during the complex analysis of the SUSI data - particularly the times of minima, which are also the times of minimum angular separation. Many of the stars have not been observed for many years, so that more recent epoch parameters are desirable. These can be more accurately obtained by photometry than by SUSI and removes the need for determining those parameters from the SUSI data.

2 New photometric data

Since SUSI was expected to be limited to fairly bright stars ($V < 6$) in its initial configuration, this photometry could be accomplished on a small telescope. The 24-inch (61 cm) telescope of the Australian National University at Siding Spring Observatory (hereinafter referred to as SSO) is ideal.

The photometer used was the Motorised Filter Box (MFB), (Shobbrook, 2000) with Stromgren y and b filters and a cooled GaAs photomultiplier. The Stromgren y narrow band filter was used because most systems were too bright for the Johnson V filter without also using a neutral density filter. The observations were reduced to the Johnson V scale using *uvby* secondary standard stars of Cousins (1987) in the E Regions. The b filter was used, with a short integration time, only in order to obtain the V magnitude using the standard stars' transformation relations from the natural to the standard magnitudes: $(by)_{\mathrm{std}}/(by)_{\mathrm{nat}}$ and $(V_{\mathrm{std}}V_{\mathrm{nat}})/(by)_{\mathrm{std}}$, where the subscripts refer to the standard system magnitudes and the MFB natural magnitudes. The new data will be referred to as 'SSOV' magnitudes. The sky aperture used for all the observations was 30 arcsec and sky background positions were carefully chosen from finding charts. The comparison stars employed for each variable are listed in Table 1.

The usual observing procedure for the program was to obtain groups of five star measurements in the symmetrical order: $C1_1$ Var_1 C2 Var_2 $C1_2$, where 'Var' is the binary star and C1 and C2 are the comparison stars. The total integration time for each y star observation was 60 seconds and the internal photometric errors were typically 0.001 to 0.003 mag (1 to 3 mmag). Mean atmospheric extinction coefficients were used for most of the nights since the airmass difference between the stars was always small and the airmass less than 2.0. After the correction for extinction and for the slopes of the transformation relations mentioned above, magnitude differences were formed as follows:

$$(\mathrm{Var}_1+\mathrm{Var}_2)/2 - (\mathrm{C1}_1+\mathrm{C1}_2)/2,$$

$$(\mathrm{Var}_1+\mathrm{Var}_2)/2 - \mathrm{C2} \text{ and}$$

$$(\mathrm{C1}_1+\mathrm{C1}_2)/2 - \mathrm{C2}\ .$$

These are effectively the mean values of Var–C1, Var-C2 and (C1–C2), respectively, during the 5-star cycle. All magnitude differences are thus at nearly the same average time. The Julian Date of the observation was taken as that of the mean time of the two 'Var' observations. Sky background observations were taken whenever necessary to ensure that the correction was accurate to 1 mmag for the faintest of the three stars in each field.

The 'five star' procedure just described was not followed when the variables were going steeply into or out of eclipse. At that time, a continuous series of up to 15 or 20 observations of the variables was often taken, alternating with observations of C1 and C2. In such cases, the individual observations were used with the magnitude of the comparison stars at the times of observation of the variable derived from a polynomial in time (i.e. JD) fitted to their magnitudes.

The heliocentric Julian dates (HJDs) and the (Variable–C1) SSOV magnitudes are listed in Table 2. The accuracy of the photometry can be seen most clearly at the times of maximum light, where the magnitudes are essentially constant for a time much longer than the duration of an observation. The above procedure generally maintained a precision of 3 to 5 mmag in the (variable minus comparison star) magnitudes. Exceptions sometimes occurred if the seeing was poor and there was a companion star close to the edge of the sky aperture, as in the case of UU Psc.

Table 3 lists the Hipparcos observations of the 20 stars, shifted by the magnitude shown in the header for each star so that the light curves can be shown on the same plots as the SSOV data. The Hipparcos catalogue's Julian dates have been corrected to heliocentric values. Figure 1 shows the light curves, including both the Hipparcos and SSOV data.

3 Discussion of individual stars

Table 1 lists the periods, heliocentric Julian dates of the primary minima and the phases of the secondary minima. Where possible, the primary minima are determined from SSOV observations made on a night when a series was taken through the minimum. The phases of the secondary minima were estimated from the complete light curve, including the Hipparcos data. For IM Mon, ψ Ori, π Sco and UU Psc, where most of the data points were from different nights, both minima were determined from all the SSOV and Hipparcos observations. The HJDs of the minima were taken from one or more observations towards the end of the 1990s.

Estimates of the periods, the heliocentric Julian dates of primary minima and the phases of secondary minima were determined from the graphs of the light curves plotted as Excel charts. The total data spread for most of the stars is over eight to ten years, so that for each star, varying the period by small increments enabled the relative fit of the SSOV and the Hipparcos data to be seen clearly on the Excel graphs at primary minimum. This might be described as 'visual robust estimation' since, especially where there are plenty of observations, those with the largest deviations tend to be given less weight. The HJD of the minima were measured from the graphs by bisecting their curves at several positions and drawing a mean line through the points thus located. The phases at which these (usually nearly constant phase) lines crossed the lowest points of the curves were taken as the times of minima. It is expected that other workers using these data will use their own favourite methods of determining these parameters.

It was often clear that the SSOV and the Hipparcos secondary minima occurred at different phases and where this is so, the phase differences are noted below. The errors quoted are estimates based on visual inspection of the relative positions of the SSOV and the Hipparcos data in the Excel charts as the orbital parameters were varied.

For some stars the period listed in Table 1 is significantly different from that in the General Catalogue of Variable Stars (Kholopov, 1985, hereafter referred to as the GCVS). In several cases, notably V539 Ara, rotation of the line of apsides is clearly the problem, since the phases of secondary minima are obviously different from 0.5, indicating a significant orbital eccentricity. The data presented here should be combined with other photometry and with radial velocity data in order to determine the apsidal motion.

3.1 V539 Ara

The best fit period for the primary minima from the GCVS to the SSOV data is 3.1691015d. However, this does not fit the Hipparcos data, suggesting that there is rotation of the line of apsides - precession of the orbit. The best period for fitting to the SSOV and the Hipparcos data is 3.1690600d

3.2 R CMa

The period is different from that in the GCVS. Although the phase of secondary minimum in the present data is close to 0.5, it is possible that the orbit has a significant eccentricity. The period in the 1990s decade does not take this into account.

3.3 ε CrA

The best fit period to the Hipparcos and SSOV observations is 0.5914435d, but there are progressive shifts of the data points from the early 1990s Hipparcos data to the later SSOV observations. The phase of secondary minimum with respect to the fixed phase zero for the primary minimum moves from 0.487 in 1999 to 0.502 in 2001, with an estimated uncertainty of +0.002 in both cases.Such unpredictable behaviour, probably largely due to transient large starspots, is observed in other W UMa stars, such as AE Phe (Niarchos & Duerbeck, 1991). Further discussion of this star is planned in a future paper.

3.4 δ Lib

The secondary minimum is only 0.1 mag deep and not detectably different in phase from 0.5.

3.5 IM Mon

The narrowness of the two minima suggests a grazing eclipse in both sets of data.

3.6 U Oph

The Hipparcos secondary minimum is slightly later, by about phase 0.002, than that from the SSOV observations..

Table 1: Binary systems and comparison stars, with mean errors.

Ident.	C1	C2	P (d)	HJD Prim. min.	Phase Sec. min.
V539 Ara	HR 6614	HR 6632	3.19706	2450643.8802	0.4695
			0.00002:	0.0010	0.0010
R CMa	HR 2705	HR 2785	1.1359500	2451197.073	0.498
			0.0000005	0.001	0.001
ε CrA*	α CrA	γ CrA	0.5914435	2452042.1110	0.502:
δ Lib	HD 133008	HR 5578	2.327351	2450661.941	0.500
			0.000002	0.002	0.005:
IM Mon	HR 2325	HR 2344	1.190240	2451189.035	0.500
			0.000002	0.002	0.005
U Oph	HR 6367	HR 6394	1.677341	2451415.9500	0.5000
			0.000002	0.0005	0.0005
VV Ori	HR 1842	HR 1871	1.4853735	2451556.999	0.499
			0.0000005	0.001	0.002
ψ Ori	HR 1842	HR 1770	2.52599	2450407.150	0.50
			0.00002	0.001	0.02
EE Peg	HR 8265	HR 8292	2.628217	2451458.979	0.500
			0.000002	0.002	0.002
ζ Phe	η Phe	(No C2)	1.6697725	2451466.9675	0.493
			0.0000010	0.0005	0.001
UU Psc	HD 1317	HR 9093	0.841650	2450386.045	0.50
			0.000020	0.015	0.01
V Pup	HR 3089	HR 3137	1.454476	2451283.0021	0.4983
			0.000002	0.0005	0.0005
VV Pyx	HR 3344	HR 3367	4.596179	2451560.890	0.4787
			0.000002	0.002	0.0005
RS Sgr	HR 6788	HR 6893	2.4156843	2451350.126	0.4980
			0.0000003	0.001	0.0005
V3792 Sgr	HR 6692	HR 6700	2.248082	2451038.036	0.500
			0.000002	0.002	0.001
V453 Sco	HR 6628	HR 6647	12.0060	2450718.97	0.500
			0.0002	0.05	0.005
V906 Sco	HR 6628	HR 6647	2.785959	2450643.175	0.525
			0.000004	0.001	0.001
μ^1 Sco	μ^2 Sco	HR 6214	1.446270	2449534.178	0.502
			0.000001	0.002	0.001
π Sco	HR 5904	HR 5917	1.570103	2452025.96	0.500
			0.000005	0.01	0.005
AL Scl	δ Scl	HR 9050	2.445094	2450737.927	0.471
		HR 9050	0.000001	0.001	0.001

*Further discussion of the ε CrA data is planned in a future publication.

3.7 VV Ori

The Hipparcos data's secondary minimum and the maximum at phase 0.7 - 0.8 especially are brighter than the SSOV data if the two data sets are fitted at the primary minimum. Conversely, if a fit is made to the secondary minimum and the following maximum, the primary minimum and the following maximum are about 0.02 mag fainter in the Hipparcos data.

3.8 ψ Ori

The depth of the primary minimum suggests a grazing eclipse.

3.9 EE Peg

Both minima are poorly defined in the Hipparcos data.

3.10 ζ Phe

The Hipparcos secondary minimum may be 0.002 of the phase later than that from the SSOV data.

3.11 UU Psc

This star has a companion 1.5 magnitude fainter at 11 arcsec distance. The SSOV data (using a 30 arcsec aperture) always included this companion by offsetting UU Psc from the centre of the aperture. However, it appears that the Hipparcos photometry may be severely affected by the companion. The brightest Hipparcos observations lie along the light curve defined by the SSOV data, but there are many observations scattered below the light curve (many even below the graph in Figure 1), presumeably due to the companion's light being only partly included.

3.12 V Pup

Through secondary minimum, the Hipparcos data have more scatter than the SSOV observations and there is no clear difference between the phases of the SSOV and the Hipparcos data minima.

3.13 VV Pyx

There are only two observations in the Hipparcos data in the minima and both are in the secondary minimum. These points (in 1990) suggest that secondary minimum is 0.0015 phase later than it was later in the decade. However, there is no indication of a progressive change in secondary phase during the decade from the more extensive SSOV data; the Hipparcos observations may instead be explained by their being approximately 0.03 magnitude too bright. Such errors may be expected, judging from the scatter in the Hipparcos data at maximum light (Figure 1).

3.14 RS Sgr

There are few observations from the Hipparcos data in the minima, and no suggestion of a phase shift in the secondary minimum with respect to the SSOV observations. The period in Table 2 has been determined from the GCVS primary minimum and the SSOV minimum – over a period of 84 years – and fits both the Hipparcos and SSOV data very well.

3.15 V3792 Sgr

The Hipparcos data's secondary minimum is poorly defined, but may be slightly later than that shown by the SSOV observations. The period has been determined from the GCVS and the SSOV times of primary minimum, differing by 25 years, and its value is not significantly different from that in the GCVS.

3.16 V453 Sco

From the GCVS primary minimum to the SSOV minimum gives the same period as that in the GCVS. The SSOV data's phase of secondary minimum is not significantly different from 0.5, although two series of Hipparcos observations near phase 0.4 lie about 0.03 mag brighter, or conversely 0.015 of the phase later, than the SSOV data .

3.17 V906 Sco

The period from the GCVS to the SSOV primary minima is 2.785949d, compared to 2.785959d from the Hipparcos data to the SSOV minimum. The Hipparcos primary minimum points are decreased in phase by about 0.02 and the secondary minimum by 0.05 with this shorter period, suggesting apsidal rotation.

3.18 μ^1 Sco

The period listed in Table 2 is determined from the GCVS to SSOV primary minima, a baseline of 17,533 days. The Hipparcos and the SSOV data fit well at both minima, but the best SSOV observation of primary minimum was only about 3 years after the Hipparcos observations and any shift of the secondary minimum during that short time is not detected.

3.19 π Sco

This star shows only an ellipsoidal variation and does not yet have a variable star designation. The variation of this star is over only 0.03 magnitude but is very clearly defined both in the Hipparcos and the SSOV observations.. Both data sets follow closely the same curve, with no detectable difference between primary and secondary minima. The SSOV (π Sco – HR 5904) data for 2001 had to be adjusted by +0.008 mag in order for the zero points to match the earlier SSO V observations, so it is possible that HR 5904 is slowly varying.

3.20 AL Scl

The ellipticity of the orbit is significant. The Hipparcos secondary minimum appears to be somewhat earlier, at phase 0.468, but the data are noisier and the minimum not so well determined as that from the SSOV data

4 Summary

The new SSOV data presented in this paper were collected between 1991 and 2001. They are combined with the data from the Hipparcos catalogue, which were taken between 1989 and 1993, for the purpose of determining the periods of these 20 variable binary stars at a more recent epoch than is available in the General Catalogue of Variable Stars (Kholopov, 1985). These recent epoch data may be combined with numerous earlier studies of these stars for a more complete determination of their periods and the precession of their orbits.

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Finding charts of 8 arcminutes square for selecting sky background areas were made from the STScI Digitized Sky Survey website. This work also made frequent use of the SIMBAD database, operated at CDS, Strasbourg, France.

I wish to thank Staszek Zola for many helpful discussions regarding treatment of the data and Leonid Berdnikov for aiding my early access to the Hipparcos Catalogue.

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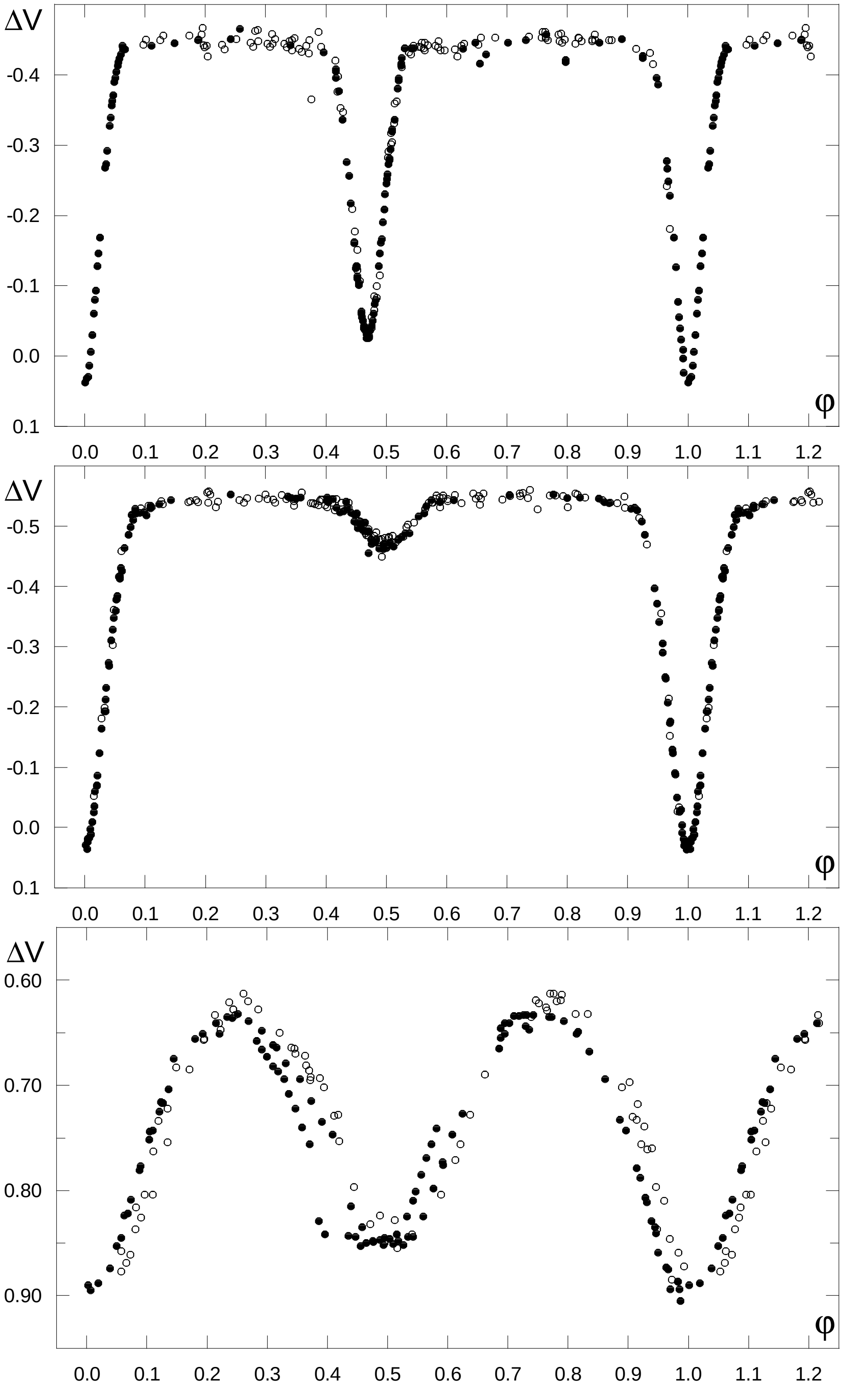

Figure 1: Top to bottom: phase diagrams of V539 Ara, R CMa and ε CrA.

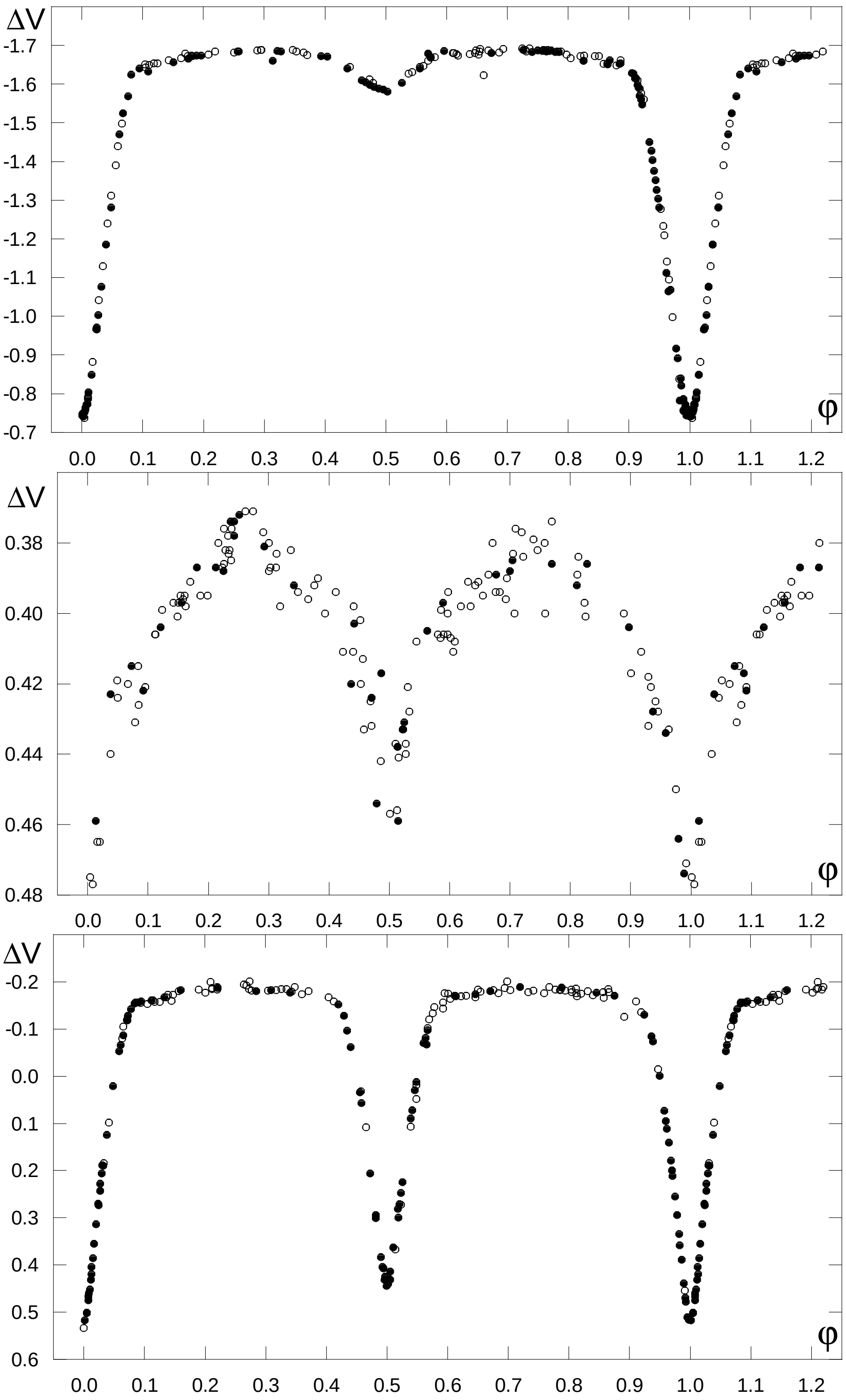

Figure 1: Top to bottom: phase diagrams of δ Lib, IM Mon and U Oph.

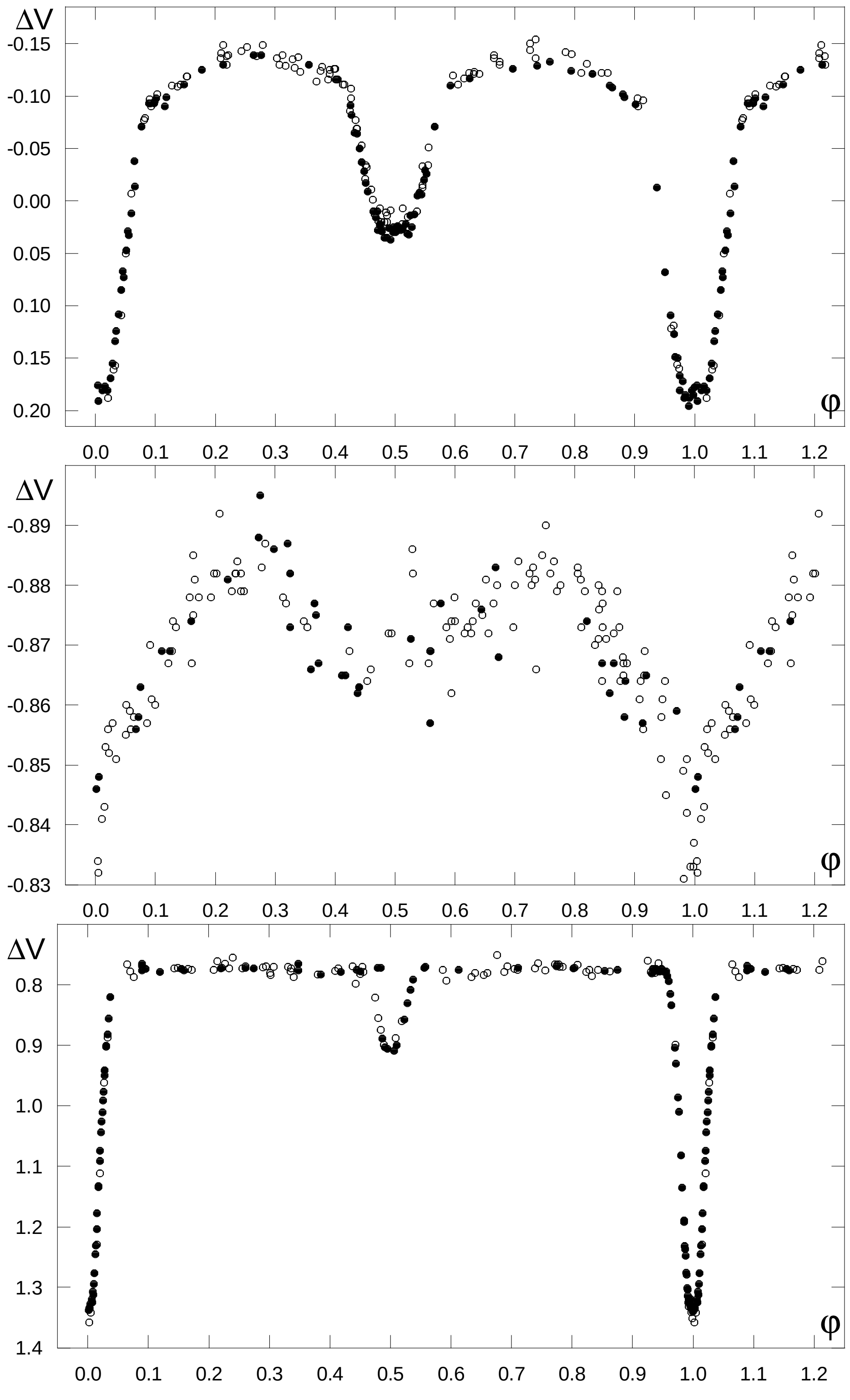

Figure 1: Top to bottom: phase diagrams of VV Ori, ψ Ori and EE Peg.

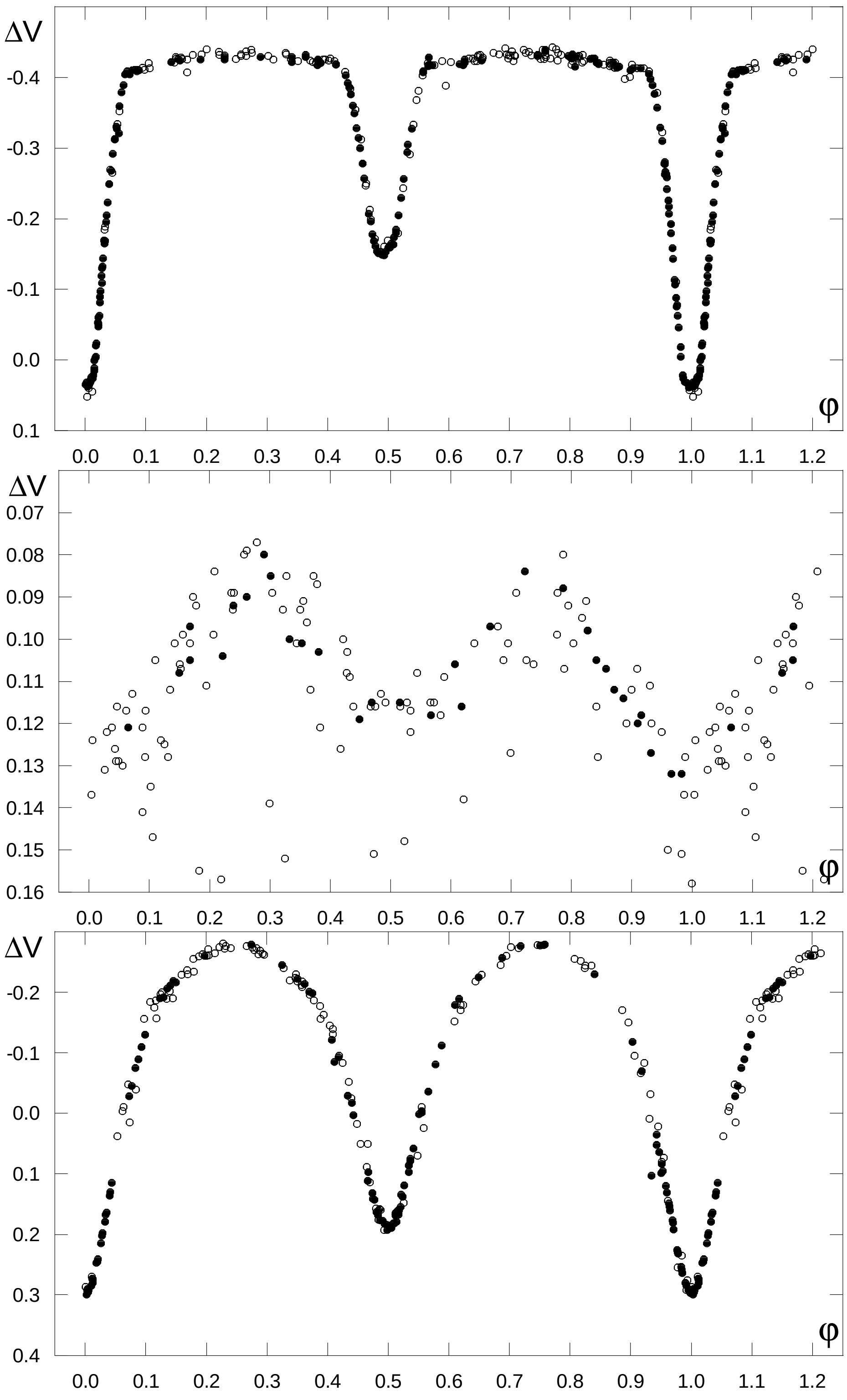

Figure 1: Top to bottom: phase diagrams of ζ Phe, UU Psc and V Pup.

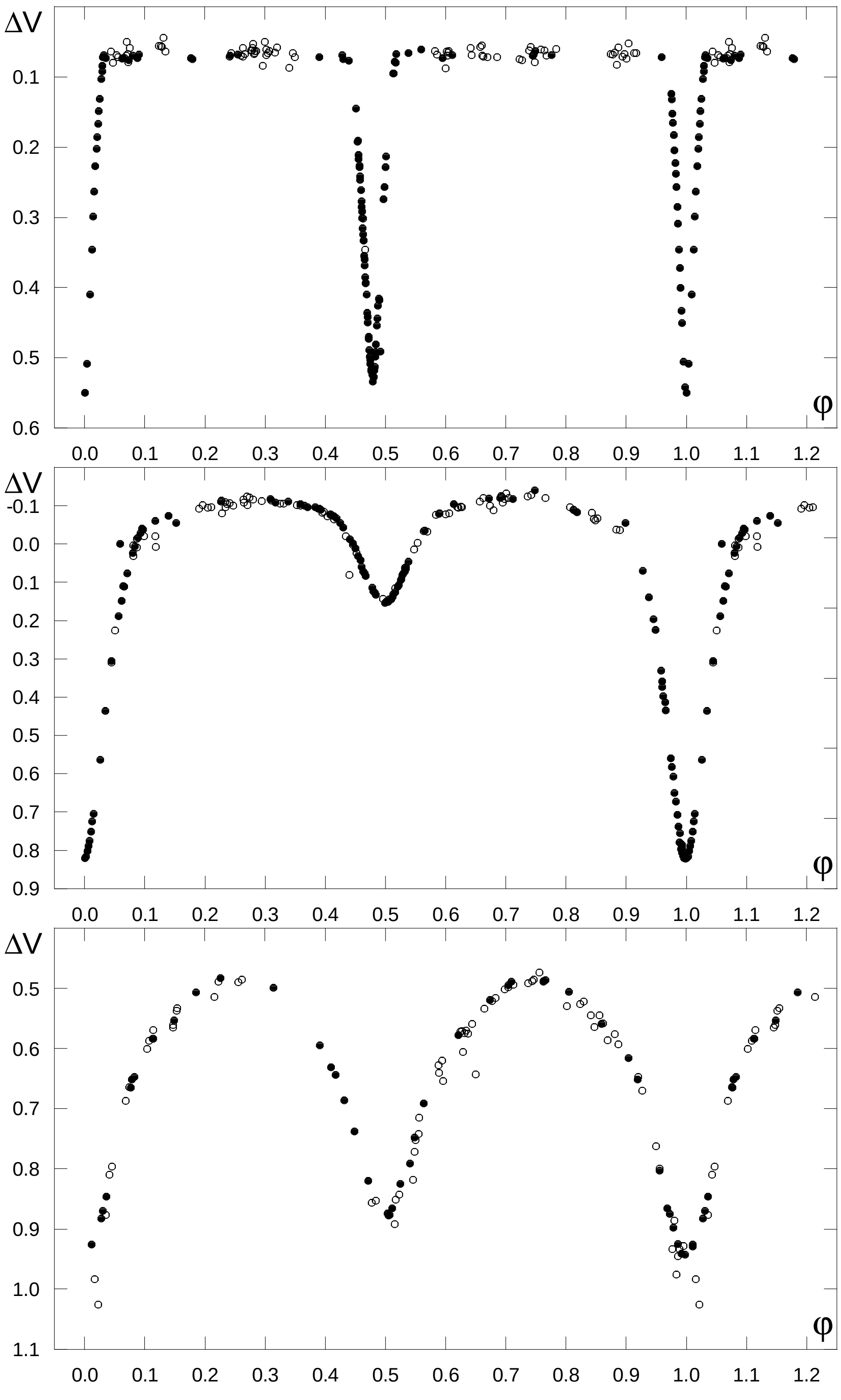

Figure 1: Top to bottom: phase diagrams of VV Pyx, RS Sgr and V3792 Sgr.

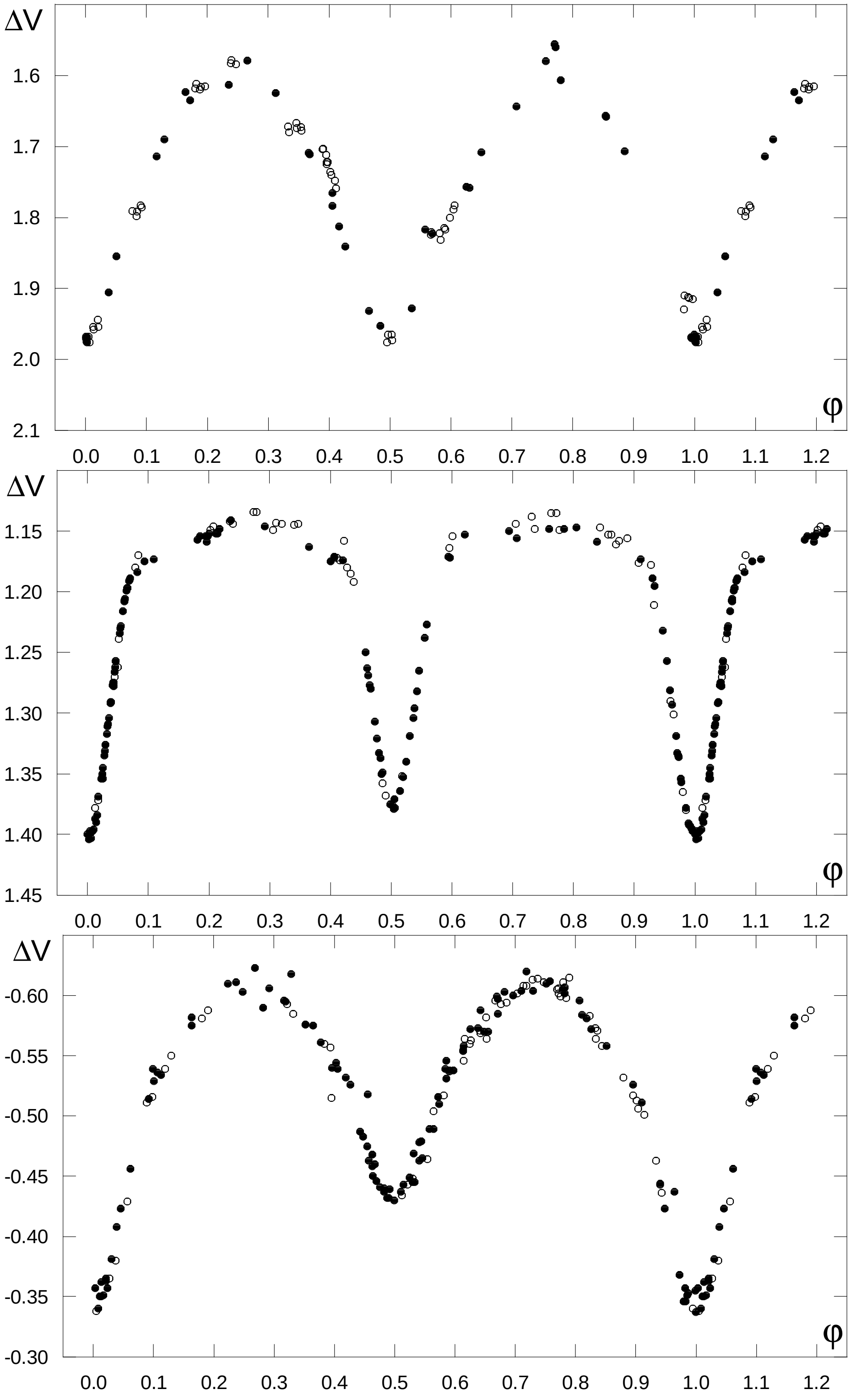

Figure 1: Top to bottom: phase diagrams of V453 Sco, V906 Sco and μ^1 Sco.

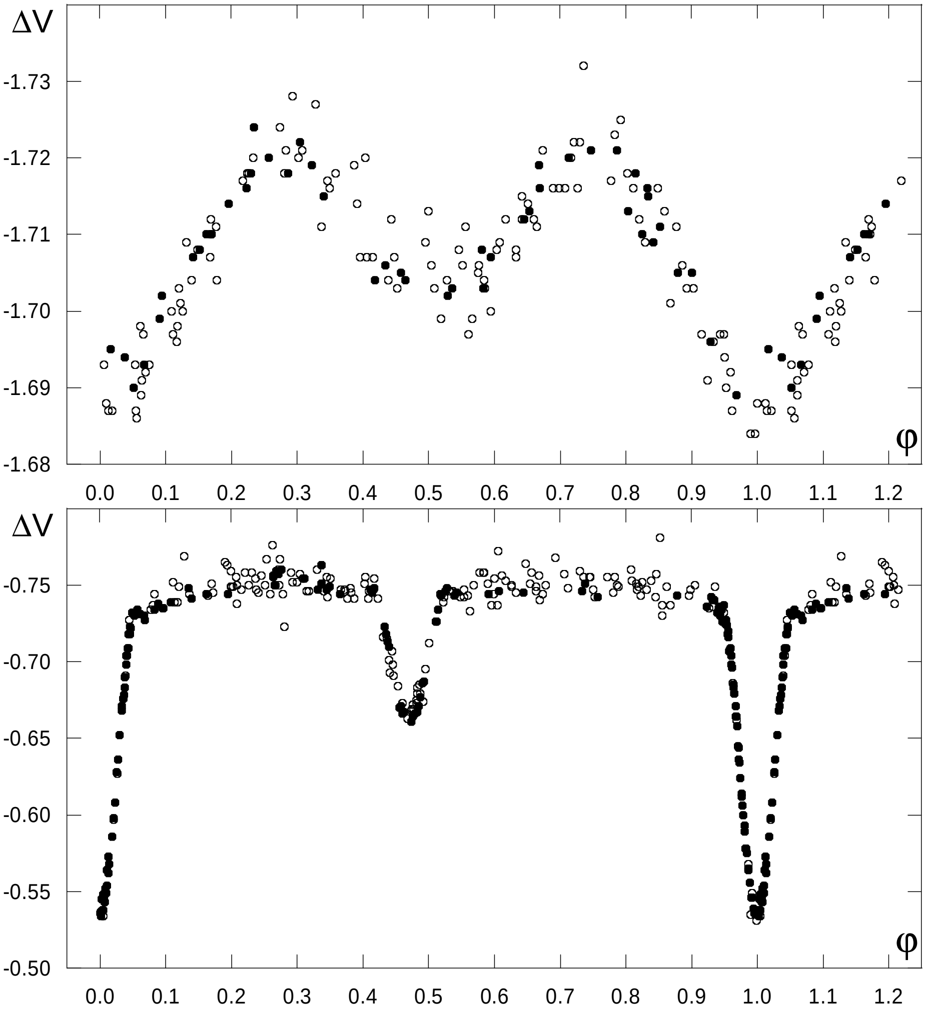

Figure 1: Phase diagrams of π Sco (top) and AL Scl (bottom).