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Deep census of variable stars in a VLT/VIMOS field in Carina⋆,⋆⋆

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ABSTRACT

Aims. We searched for variable stars in deep V-band images of a field towards the Galactic plane in Carina.

Methods. The images were taken with the VIMOS instrument at ESO VLT during 4 contiguous nights in April 2005. We detected 348 variables among 50 897 stars in the magnitude range between $V = 15.4$ and $V = 24.5$ mag. After detection, we classified the variables by a direct eye inspection of their light curves.

Results. All variable objects besides 9 OGLE transits in the field are new discoveries. We provide a complete catalog of all variables, which includes eclipsing/ellipsoidal binaries, miscellaneous pulsators (mostly δ Scuti-type variables), stars with flares, and other (irregular and likely long-period) variables. Only two of the stars in our sample are known to host planets.

Conclusions. Our result has implications for future large variability surveys.

Key words. stars: variables: general – stars: variables: delta Sct – binaries: eclipsing – stars: flare – planetary systems – stars: statistics

1. Introduction

Variable stars provide important information about the nature and evolution of stars in various regions of our Galaxy. Eclipsing binary stars provide us information about the masses and radii of stars (see e.g., Huang & Struve 1956; Popper 1985). For some, i.e. the detached systems, it is possible to measure distances (Paczyński 1997), which is particularly useful in the case of star clusters (see e.g., Bonanos et al. 2006; Kaluzny et al. 2007). Pulsating variables, such as Cepheids and RR Lyrae, serve as such distance indicators (e.g., Benedict et al. 2007; Feast et al. 2008). The type of pulsators known as δ Scuti stars offer unique insight into the internal structure and evolution of main-sequence objects (Thompson et al. 2003; Goupil et al. 2005).

Following the advent of large-scale wide-field photometric surveys, the number of new variables has increased rapidly. The surveys are usually dedicated to the detection of particular objects, such as transiting extrasolar planets, microlensing events, or gamma ray burst afterglows, e.g., MACHO (Alcock et al. 2000) and OGLE surveys (Udalski et al. 2003). Most of the wide-field surveys are conducted with small (less than 0.5 m) robotic telescopes, such as ASAS (All-Sky Automated Survey, Pojmański 2001), and ROTSE (Robotic Optical Transient Search Experiment, Woźniak 2004), allowing the search for variability only for bright stars (down to ∼15 mag in the V band). Until recently, large telescopes, i.e., those of 4–10 m in diameter, have focused instead on individual objects, because of their small fields of view. Practically, there have been very few long and deep variability surveys. In this paper, we present the results of searches for variable objects in deep imaging (down to $V \approx 24.5$ mag) of a Galactic field in the constellation of Carina, based on data collected with an 8-m telescope for 4 continuous nights. Our results show the great potential of upcoming large visual and near-infrared surveys, such as LSST (Large Synoptic Survey Telescope, Ivezić et al. 2008), VVV (Vista Variables in Via Lactea, Ahumada & Minniti 2006), or Pan-STARRS (Kaiser et al. 2002).

2. Observations and data reduction

Observations were carried out with VIMOS at the Unit Telescope 3 (UT3) of the European Southern Observatory Very Large Telescope (ESO VLT) located at Paranal Observatory from April 9 to 12, 2009. VIMOS is an imager and multi-object

⋆ Based on observations collected with the Very Large Telescope at Paranal Observatory (ESO Programme 075.C-0427(A), D.M. and J.M.F. visiting observers).

⋆⋆ Time series tables, period and aplitude table are only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/503/651

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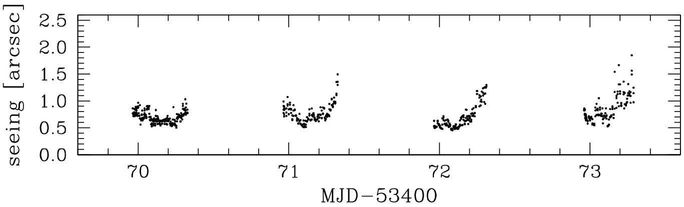

Fig. 1. The seeing during the four observing nights.

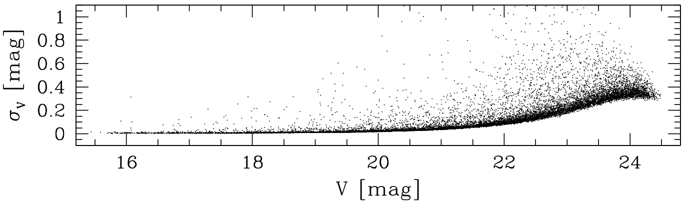

Fig. 2. The photometric errors for 12 571 stars from the VIMOS quadrant *A*2 plotted as a function of *V* magnitude.

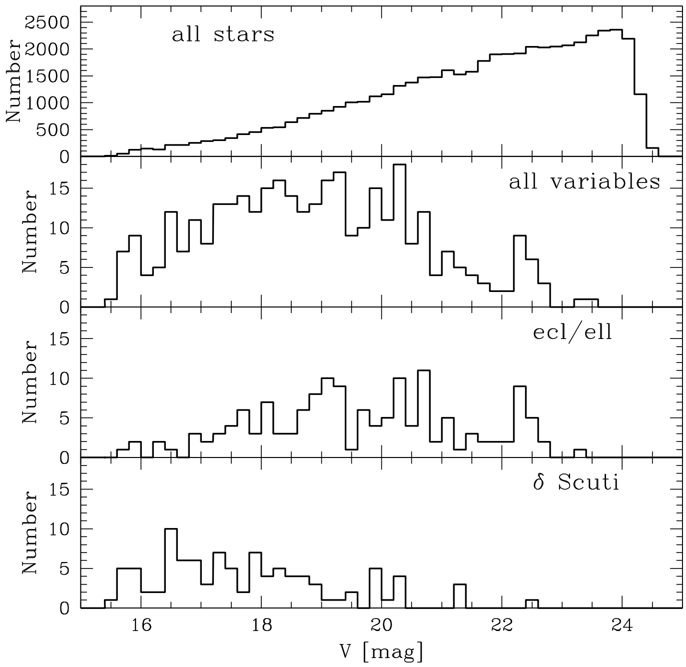

Fig. 3. Magnitude distribution of all analysed stars (50 897 objects), all detected variables in the sample (348 objects), all stars classified as eclipsing/ellipsoidal binaries (148 objects), and all δ Scuti stars (99 objects). The bin size is 0.2 mag.

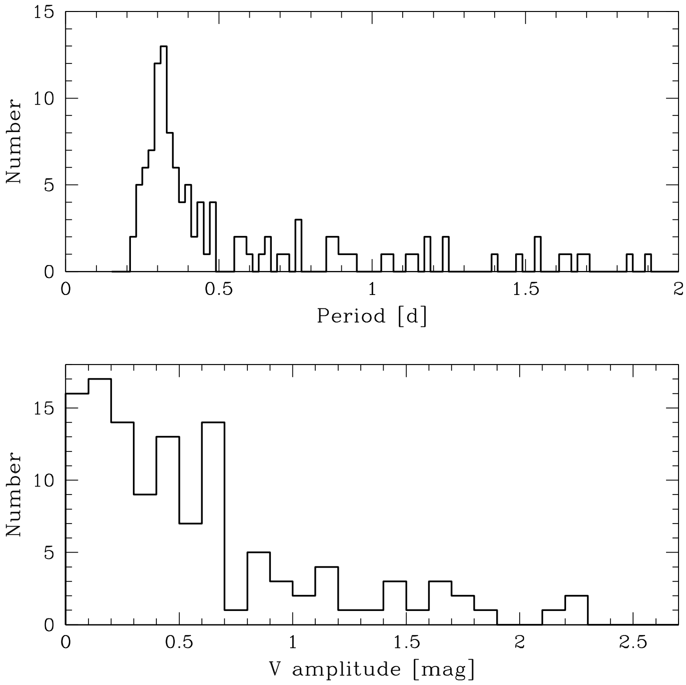

Fig. 4. Period distribution (*upper panel*) and amplitude distribution (*lower panel*) for eclipsing binaries with estimated period.

spectrograph (LeFevre et al. 2003). Its field of view consists of 4 quadrants of about $7' \times 8'$ each, separated by a cross, $2'$ wide. The CCD size is 2048×2440 pixels with a pixel size of $0\farcs205$.

The main goal of the program was to complete photometric follow-up of over 30 OGLE transiting candidates. Some individual results were published by Fernández et al. (2006), Díaz et al. (2007), Hoyer et al. (2007), Minniti et al. (2007), Díaz et al. (2008), and Pietrukowicz et al. (2009). The field analyzed in this paper is one out of four VIMOS fields monitored during the run, and is the only one which was observed during 4 full nights. Equatorial coordinates of the center of the field are RA(2000.0) = $10^h52^m56^s$, Dec(2000.0) = $-61°28'15''$, or $l = 289\fdg269$, $b = -1\fdg783$. The field contains 9 OGLE transits, two of which were confirmed to be caused by planets: OGLE-TR-111b (Pont et al. 2004) and OGLE-TR-113b (Bouchy et al. 2004; Konacki et al. 2004). All 4 nights were clear throughout, with sub-arcsecond seeing during most of the time (see Fig. 1). The dataset consists of 660 images taken only in the *V*-band.

The periphery of each quadrant suffers from coma. Therefore, for our analysis we cut out a slightly smaller area of 1900×2100 pixels, covering $7\farcm18 \times 6\farcm49$. The total field in which we searched for variable objects equals 186.3 arcmin^2.

The photometry was extracted with the help of the *Difference Image Analysis Package* (DIAPL) written by Woźniak (2000) and modified by W. Pych[1]. The package is an implementation of a method developed by Alard & Lupton (1998). To obtain higher quality photometry, we divided the field into 475×525 pixel subfields.

Reference frames were constructed by combining 8 or 9 of the highest quality individual images (depending on the quadrant). The profile photometry for the reference frame was extracted with DAOPHOT/ALLSTAR (Stetson 1987). These measurements were used to transform the light curves from differential flux units into instrumental magnitudes, which were later transformed into standard *V*-band magnitudes by adding an offset derived from *V*-band magnitudes of the planetary transits located in the field (Díaz et al. 2007; Minniti et al. 2007). The quality of the photometry is illustrated in Fig. 2. In this figure, we plot the standard deviation *versus* the average magnitude for stars from one of the VIMOS quadrants.

Because of the short period of the observations, we decided to look for variables initially by direct eye inspection of all 50 897 light curves. For comparison and more reliable statistics, we performed an independent period search with the TATRY code (see Schwarzenberg-Czerny 1989, 1996). After the automatic search, we sorted all stars in order of decreasing the

[1] The package is available at `http://users.camk.edu.pl/pych/DIAPL/`

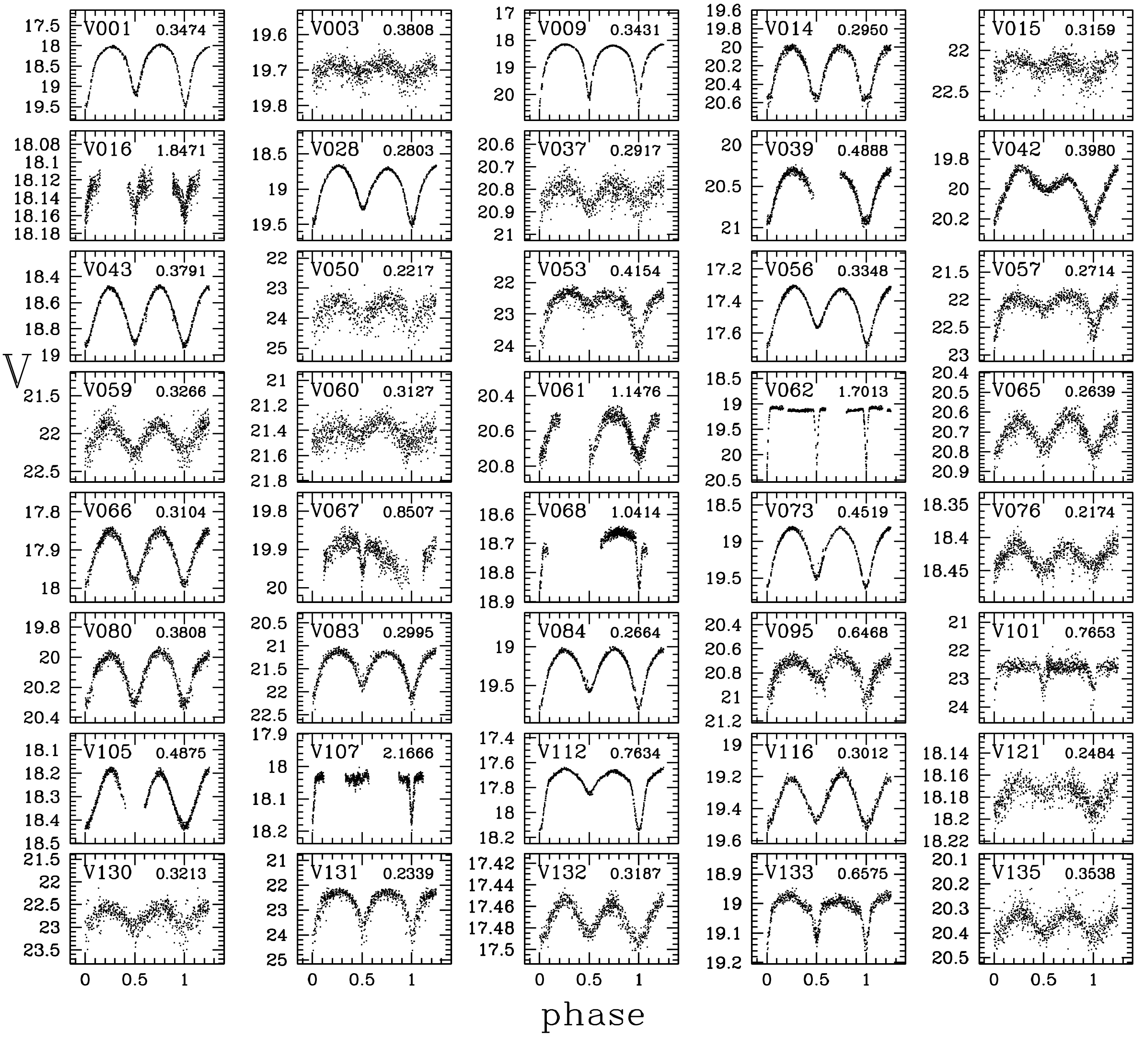

Fig. 5. Light curves for eclipsing or ellipsoidal variables with estimated periods (part 1 of 3). The identifications and periods in days are given for each object.

variability (quality) factor generated by the code, and we considered at the most promising light curves. The total number of detected variables reached 348 objects. Interestingly, among 175 periodic variables except δ Scuti stars, only four additional variables were found, and up to 51 variables were missed by automatic search compared to the by-eye method. The missing objects were mostly faint ($V > 19$ mag) low-amplitude ($\Delta V < 0.15$ mag) stars.

Finally, all detected variables were sorted by increasing right ascension and classified by considering at the shape of the light curves and their possible periods.

3. The variables

Figure 3 shows four histograms representing the magnitude distributions for all stars, all variables, eclipsing/ellipsoidal binaries, and δ Scuti stars, respectively. The distribution for the complete sample of variable stars peaks at $V \approx 18.5$ mag. The number of eclipsing/ellipsoidal variables starts to decrease below approximately $V = 19.5$ mag, but many faint objects of this type were still detected because of their high amplitudes. For δ Scuti stars, which have typical amplitudes of 0.02–0.06 mag, the detection efficiency seems to peak at $V \approx 17$ mag. Very few stars of this type were found to be fainter than $V = 20$ mag.

3.1. Eclipsing variables

In Fig. 4, we show the period and amplitude distributions for eclipsing/ellipsoidal binaries. The distribution for the shortest periods could be fit by a Gaussian with a mean period of 0.31 d. This value differs slightly from the mean value of 0.277 d and

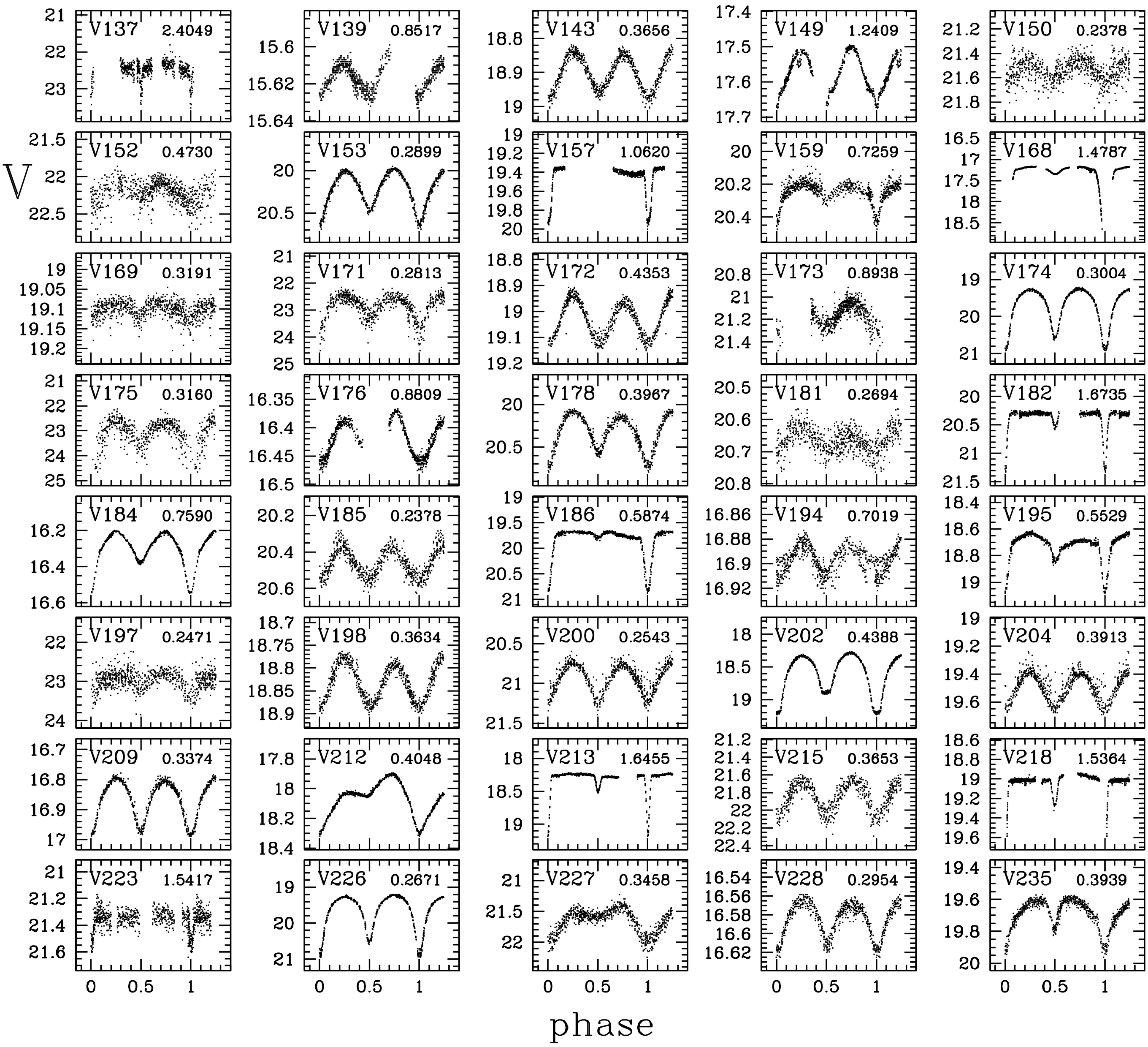

Fig. 6. Light curves for eclipsing or ellipsoidal variables with estimated periods (part 2 of 3).

σ = 0.036 d found by Weldrake & Bayliss (2008) for a Galactic plane field in Lupus, and the value of 0.37 d derived from ASAS data (Paczyński et al. 2006). From the amplitude distribution, we conclude that about three fourths of the sample binaries have V amplitudes below 0.7 mag.

The following figures, Figs. 5–7, illustrate phased light curves for all 121 eclipsing/ellipsoidal variables, for which we were able to derive accurate periods. We note that the faintest eclipsing variable found in our data, V050, has a maximum brightness of about 23.3 mag and an amplitude of ≈1.4 mag in V. System V009 has the largest amplitude of 2.23 mag. Variable V149 shows short and shallow eclipses besides the sinusoidal changes in its brightness. It may be an RS CVn binary, but more data is needed to answer question about its nature. Variable V278 corresponds to the transit OGLE-TR-109 phased with the transiting period of 0.589127 d. The analysis of the photometric data of Fernández et al. (2006), and the high-resolution spectroscopic data of Pont et al. (2005), leaves the nature of the object unclear. Two scenarios are possible: OGLE-TR-109 can be either a blend of the star with a background eclipsing binary or a transiting planet (which is less likely because of its very short period).

In Fig. 8, we present the light curves of stars showing one or two eclipses, but for which the time-span of our observations was not sufficient to estimate the period. Some variables in this sample need further explanation. Star V314 is known as the transit OGLE-TR-106 with a period of 2.53585 days (Udalski et al. 2002). Pont et al. (2005) show that this object is not a transiting planet but an eclipsing binary whose one of the companions is a low mass M dwarf with 0.116 ± 0.021 $M_{\odot}$.

Object V041 changed its brightness by about 0.25 mag showing an unexpected flat-bottom eclipse during the second night. This eclipse lasted about 4.5 h, had an amplitude of ~0.05 mag, and suggests a periodicity in the object. The overall shape of the light curve is indicative of a periodic behavior,

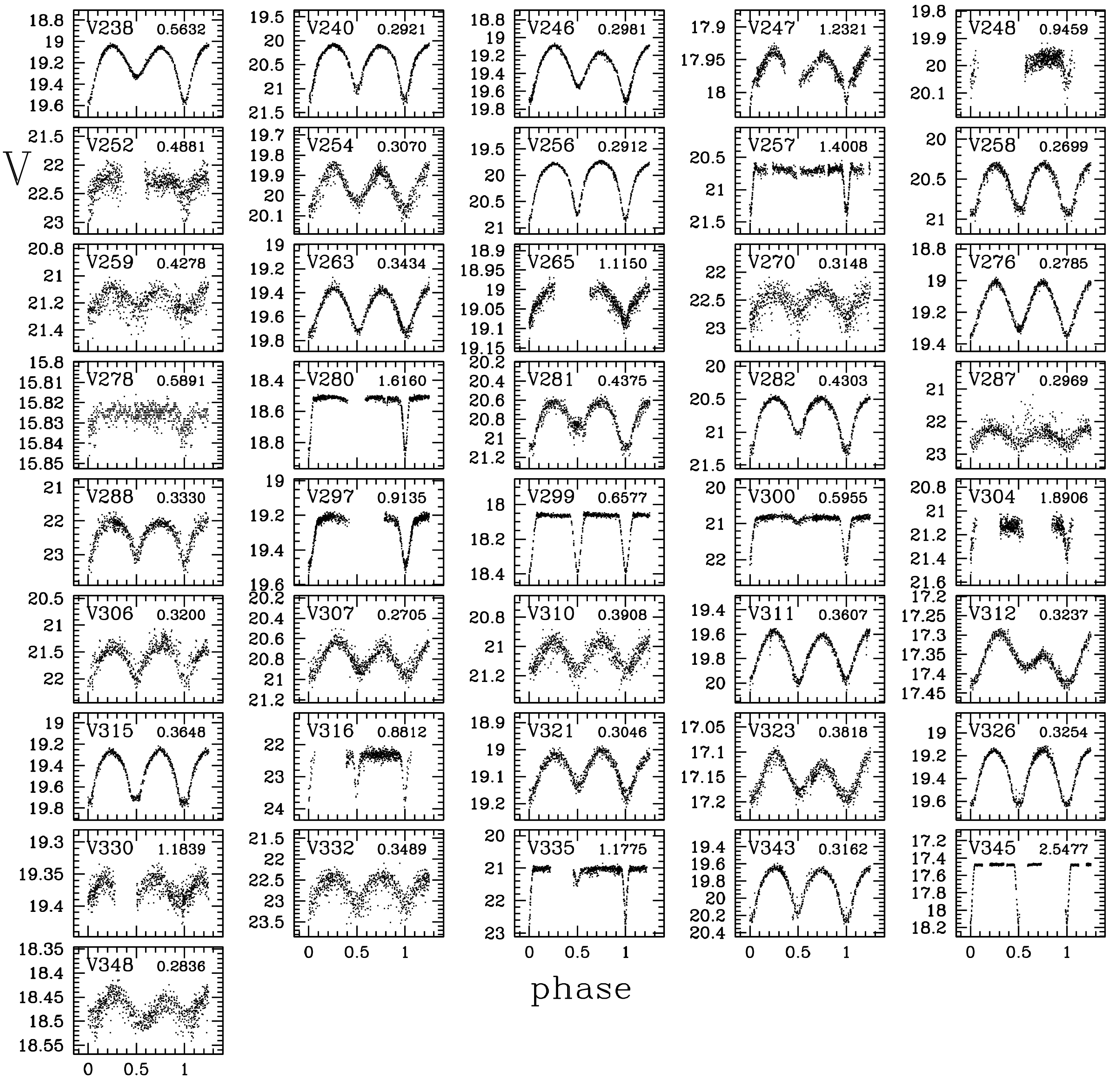

Fig. 7. Light curves for eclipsing or ellipsoidal variables with estimated periods (part 3 of 3). Note that the object V278 is the OGLE transit TR-109 phased with a transiting period of 0.589127 d.

too. Based on the incomplete photometric data, we can only speculate about the nature of the variable by asking several questions. Is this object an eclipsing binary containing a primary pulsating star, or is it just a blend? Was the observed eclipse a transit of a planetary/low-luminosity object or the secondary eclipse of a binary system? If it is indeed a true binary, what are the parameters of the components? More data are needed to find answers in this very interesting case.

The light curve of eclipsing variable V224 features some kind of bumps occurring regularly toward the end of every night. The bumps are caused by the diffraction spikes of a nearby saturated star.

3.2. Pulsating variables

We classified 99 stars as δ Scuti type pulsators. Their light curves are shown in Figs. 9–11. The amplitudes of all the stars except V340 are in the range between 0.015 and 0.230 mag. The variable V340 has an exceptionally large amplitude of about 1.0 mag. We do not attempt to derive exact periods, since most of the stars are multiperiodic variables, and hence require more sophisticated analysis, which will be the subject of future studies.

Results for other pulsating variables are shown in Figs. 12, 13. The periods of the variables range between 0.2307 and 4.1527 days. Variables V010, V018, V038, V049, V086, V098,

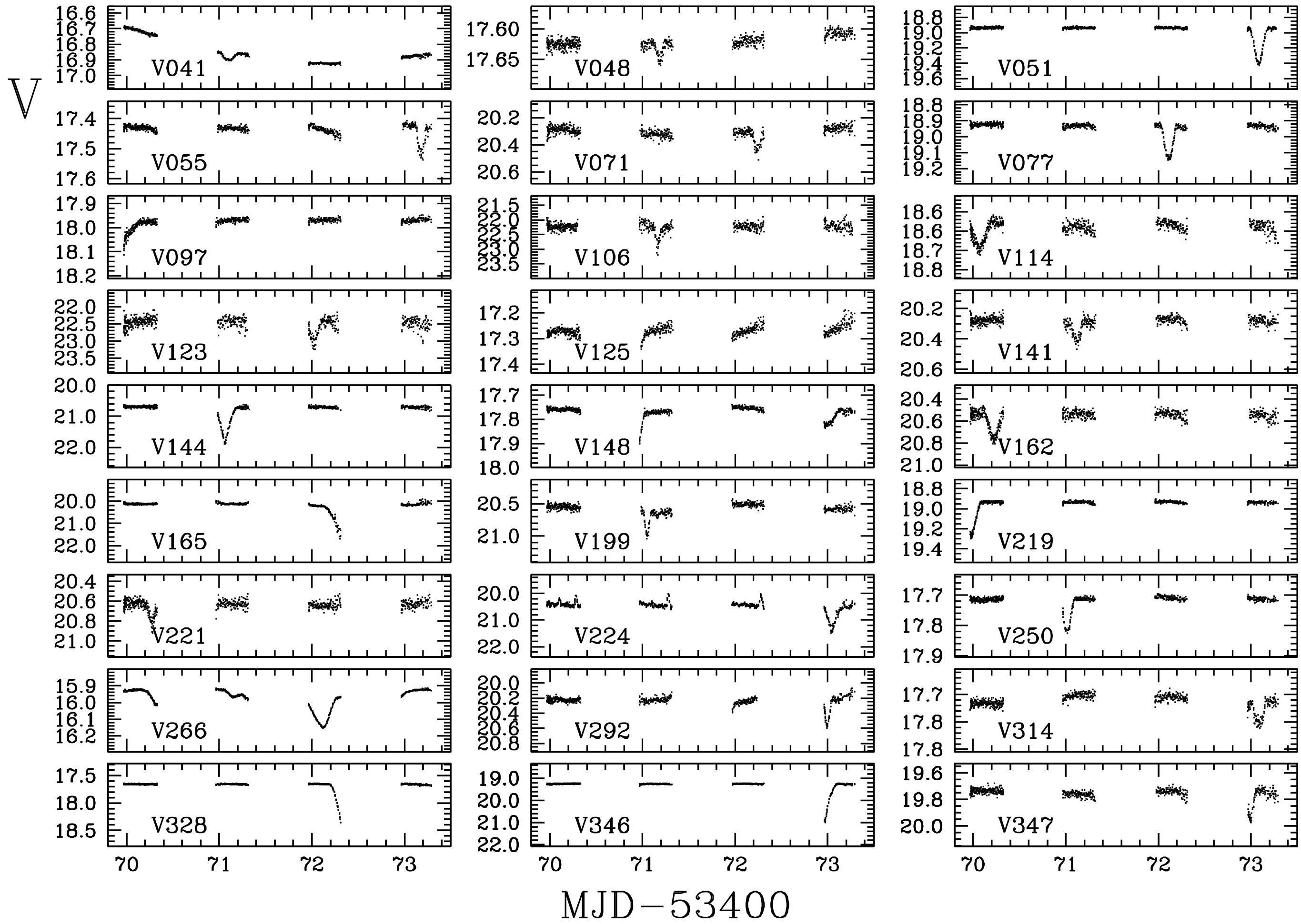

Fig. 8. Light curves for other eclipsing variables. Note that the object V314 is the OGLE transit TR-106 with an M dwarf star as a component.

Table 1. Photometric information about flares detected in seven stars.

Star	V [mag]	ΔV [mag]	Duration [h:m]	Remarks
V006	17.95	0.33	1:40	
V007	22.70	2.90	1:35	
V033	19.32	0.20	0:55	periodic, $P = 1.1625$ d
V082	19.47	0.15	0:55	
V094	23.50	2.20	1:55	
V261	19.75	0.13	0:55	
V294	19.92	0.62	2:50	

Table 2. Number of variables of different types found in the data.

Type of stars	Number	Percentage
All stars searched for variability	50 897	100%
All known variables in the field	352	0.692%
All variables detected in our survey	348	0.684%
All eclipsing	148	0.291%
Eclipsing with known period	121	
Other eclipsing	27	
Pulsating variables	153	0.301%
δ Scuti	99	0.195%
Other pulsating	54	
Other variables	39	
Stars with flares	7	0.014%
Planetary transits	2	0.004%
Variables not detected (OGLE transits)	4	

V102, V160, V222, V251, and V342 are good candidates to be RR Lyrae stars, whereas variables V012, V090, V231, and V339 are probably distant Cepheids. Light curves of miscellaneous variables are shown in Fig. 14. For example, variables V017, V029, V030, V128, V233, V241, and V302 are good long-period candidates.

3.3. Stars with flares and planetary transits

Light curves of seven stars with flares are shown in Fig. 15. Table 1 summarizes the photometric information about these stars. The amplitudes of flares in the cases of V007 and V094 are larger than 2.0 mag, while in the other five cases they are smaller than 1.0 mag. The fading part of the flare in V294 shows a kind of knee. Star V033 is periodic with $P = 1.1625$ d (the phased light curve is shown in Fig. 12).

Finally, Fig. 16 presents our own photometry of two planetary transits: OGLE-TR-111 (Pont et al. 2004) and OGLE-TR-113 (Bouchy et al. 2004). Both of them are caused by hot Jupiters. For details of the photometry of the transits, we refer to Pietrukowicz et al. (2009).

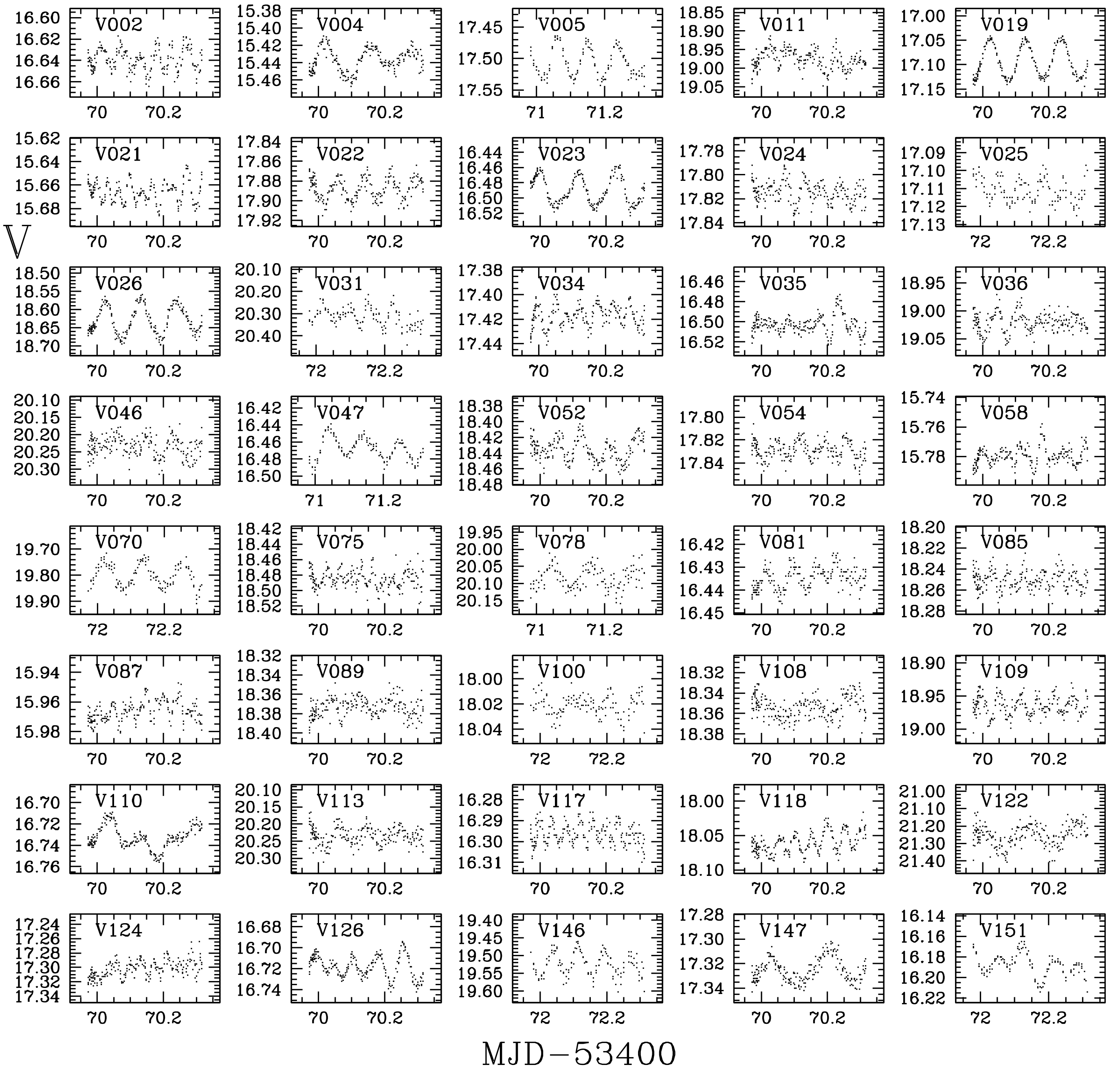

Fig. 9. Light curves for detected δ Scuti-type variables (part 1 of 3). Each panel presents only data points from a single night.

4. Conclusions

A search for variable objects in a VIMOS field targeting the Galactic plane in Carina has detected of 348 variables among 50 897 stars a faintness level of $V = 24.5$ mag. Only five of the objects were previously known to be variable, i.e., OGLE transits TR-106, TR-109, TR-110, TR-111, and TR-113. The last two transits were confirmed to be caused by hot Jupiters, while the first three appear to be binary stars. We note that four other OGLE objects are in the same field (TR-105, TR-108, TR-114, and TR-198), but no variability was detected for them during our observations. Table 2 provides statistical information about the variables found[2].

About half of the detected variables are eclipsing or ellipsoidal binaries, while the other half are pulsating variables of different types, mostly δ Scuti stars. Based on the numbers in Table 2, one can say that about seven stars in every 1000 exhibit detectable brightness variations. On average, three of them are eclipsing/ellipsoidal binaries, while three are pulsating variables (where two are usually δ Scuti stars). Other variable objects in the sample exhibit changes on longer time scales (of more than 4 days) or represent transient events (stars with flares and transits).

We emphasize that the VIMOS observations lasted only 4 nights, and we were therefore unable to detect variable objects

[2] All photometric data, finding charts, and a large table with equatorial coordinates, periods, magnitudes, and amplitudes of the variables are available via anonymous ftp to ftp.astro.puc.cl/pub/pietruk/VIMOSvar/ or cdsarc.u-strasbg.fr

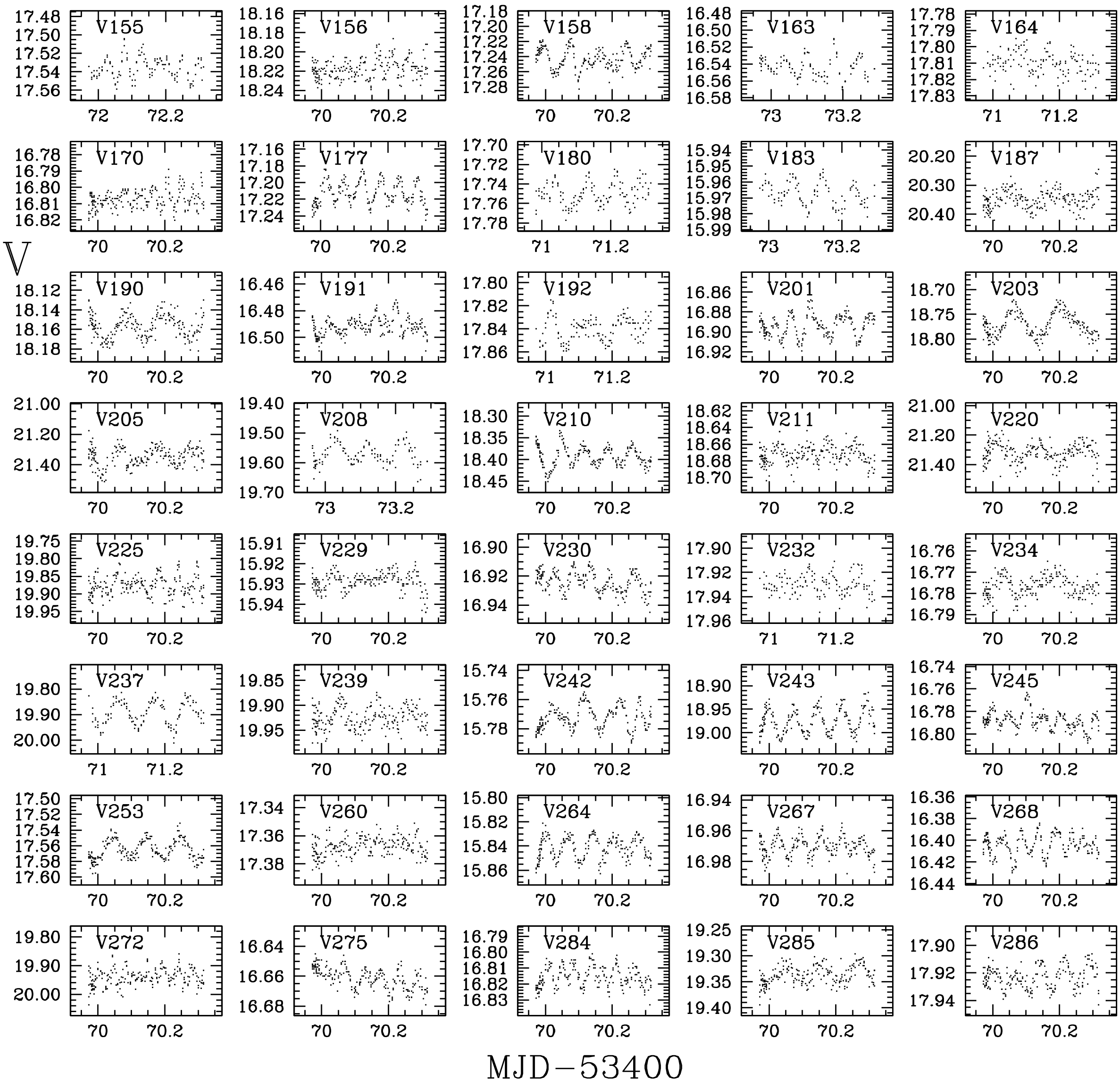

Fig. 10. Light curves for detected δ Scuti-type variables (part 2 of 3).

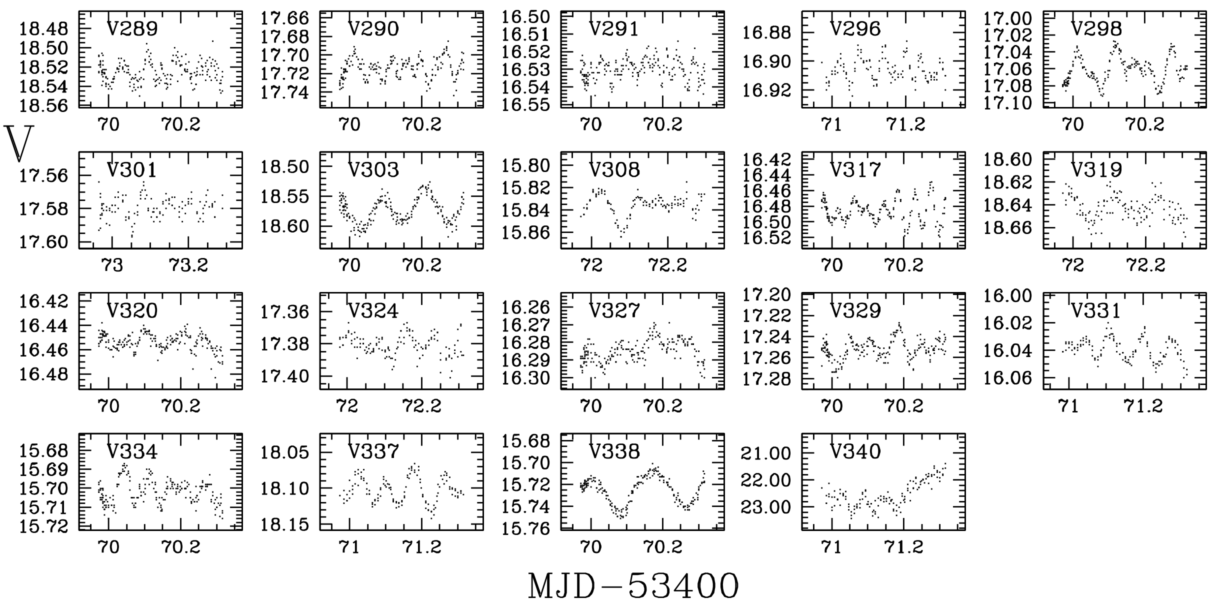

Fig. 11. Light curves for detected δ Scuti-type variables (part 3 of 3).

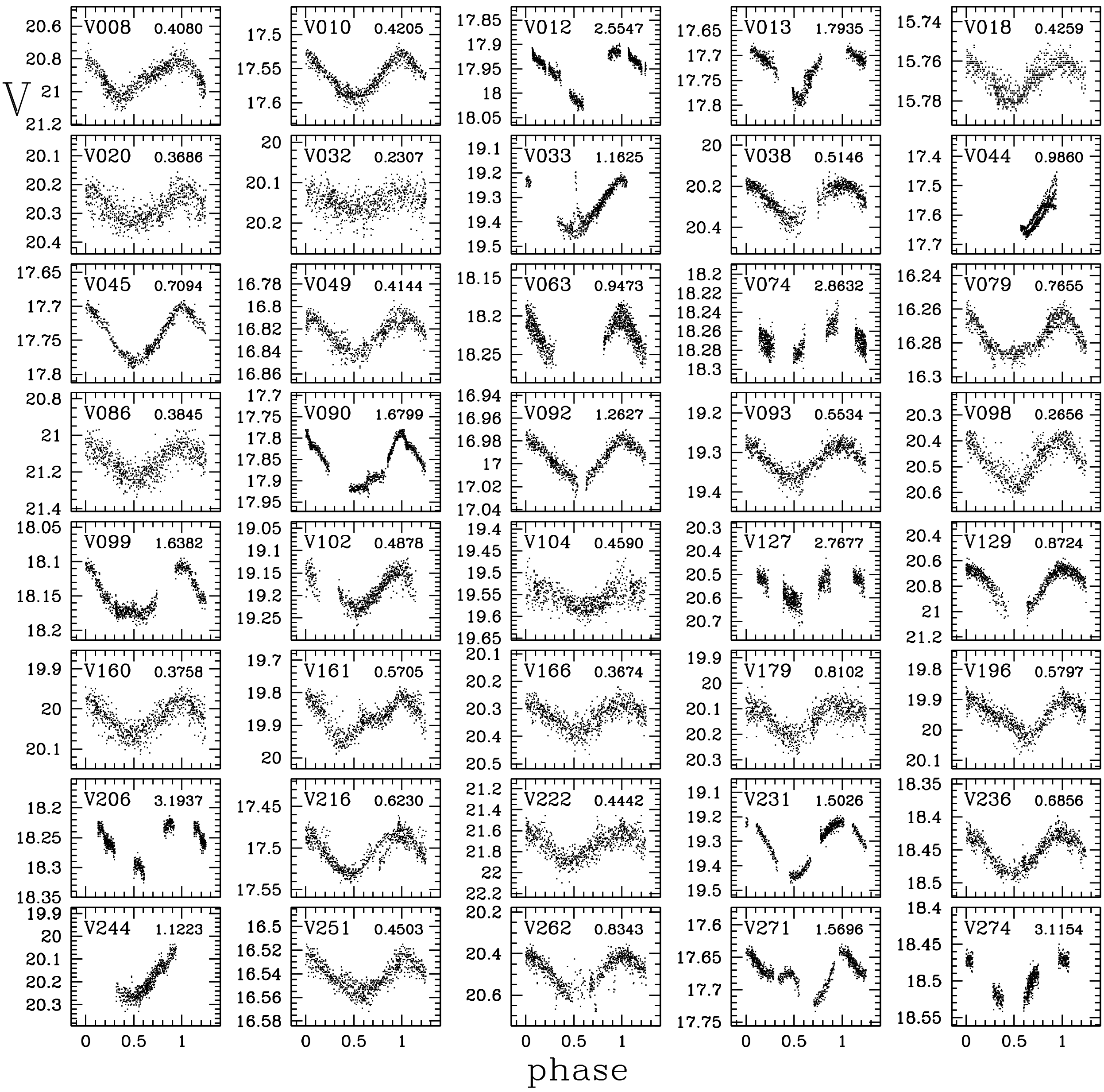

Fig. 12. Phased light curves for other pulsating variables with estimated periods (part 1 of 2). The identifications and periods in days are given for each object.

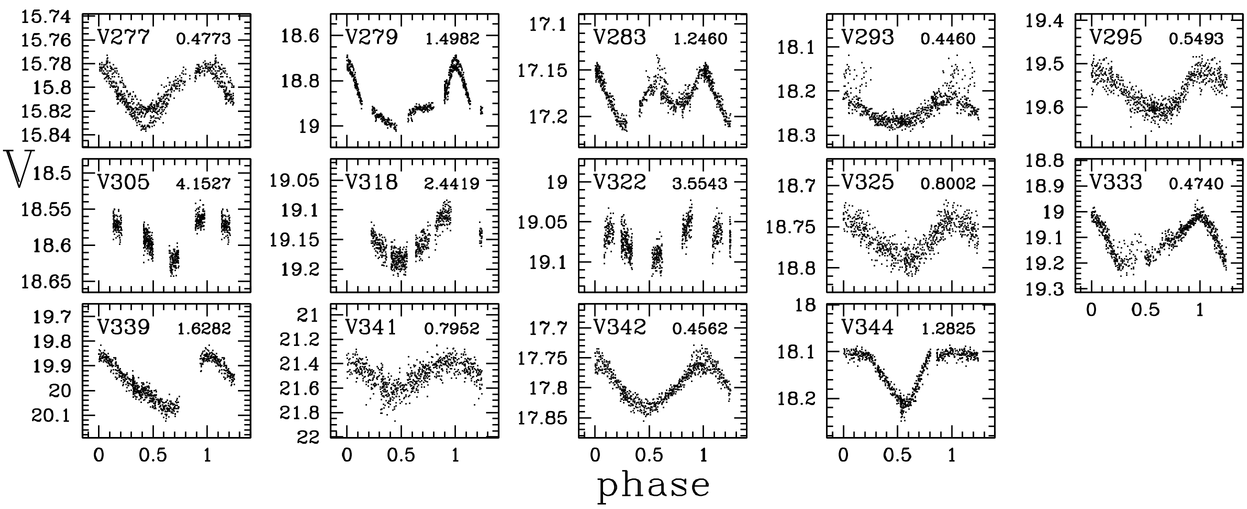

Fig. 13. Phased light curves for other pulsating variables with estimated periods (part 2 of 2).

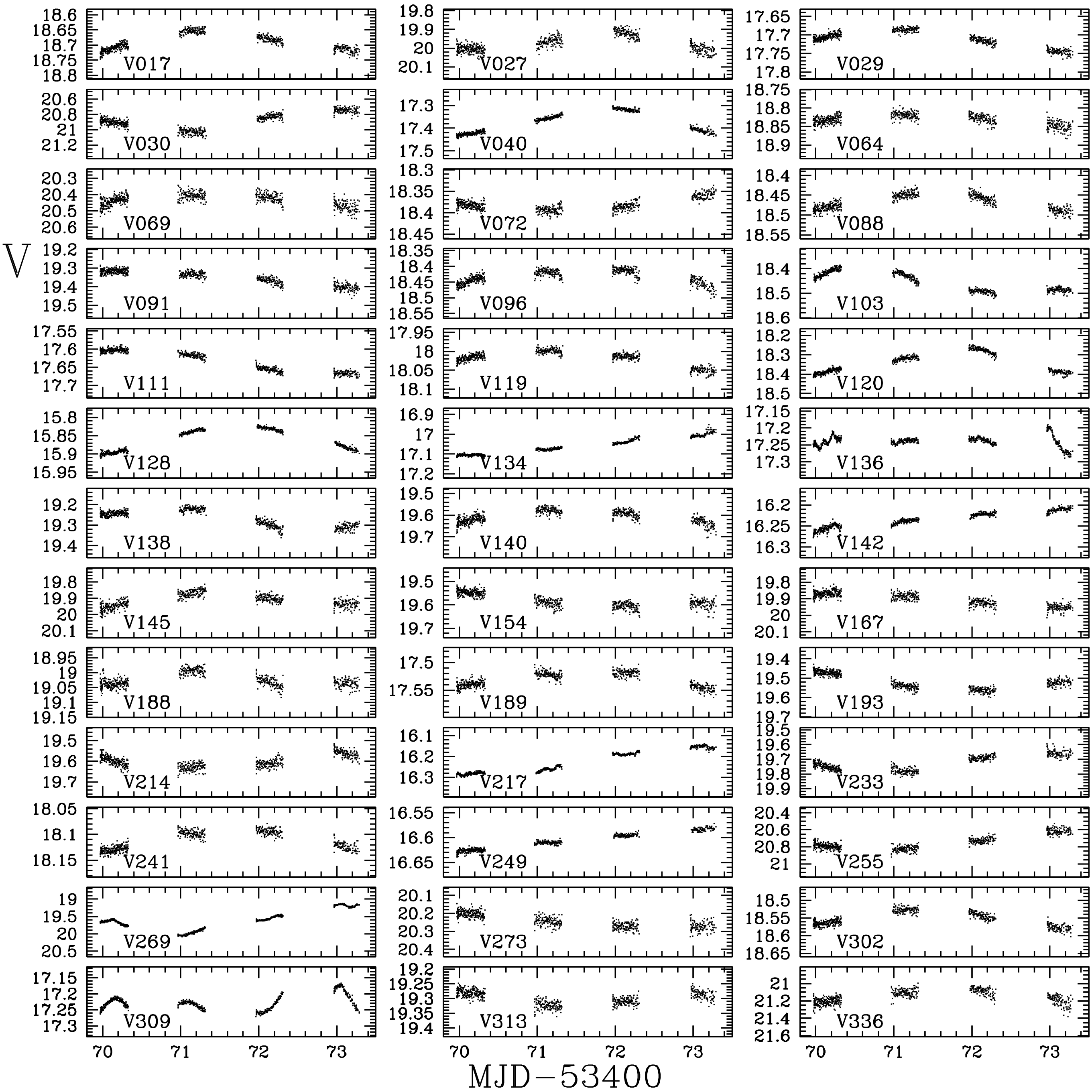

Fig. 14. Light curves of other variable objects. Most of them are likely long-period variables.

with longer time scales. Long periods are often present in red giants, which are bright and easily detectable.

There has not been any other such deep and of similar time-span and time-resolution variability survey so far from the ground. However, we can compare with other two long-term but shallower ground-based surveys that have been published. For example, Weldrake & Bayliss (2008) found 494 variables in the sample of 110 372 stars in Lupus, what corresponds to ~0.45%. The percentage of detected variables in the ASAS survey (Paczyński et al. 2006) is only 0.29%. There, among 17 000 000 stars, 50 099 were found to vary in brightness. The percentage of variables detected in our work, ~0.69% of all the stars in the sample, is much higher than in the two surveys. Also, one must remember that this is only a lower limit to the variable detection. A deep Hubble Space Telescope survey dedicated to finding planetary transits was carried out by Sahu et al. (2006). This database would sample faint variables in the Galactic bulge, useful for comparison with the present work.

We decided to search for variables by eye initially because of the short period of the VIMOS observations. It is obvious that this method will be inefficient in the case of hundreds of thousands of stars monitored for hundreds of nights. Our variable star search was later automated, yielding similar results. The present results, including the large number of newly detected variables of different types in a limited field, high quality photometry, and high accuracy of the determined periods, show that

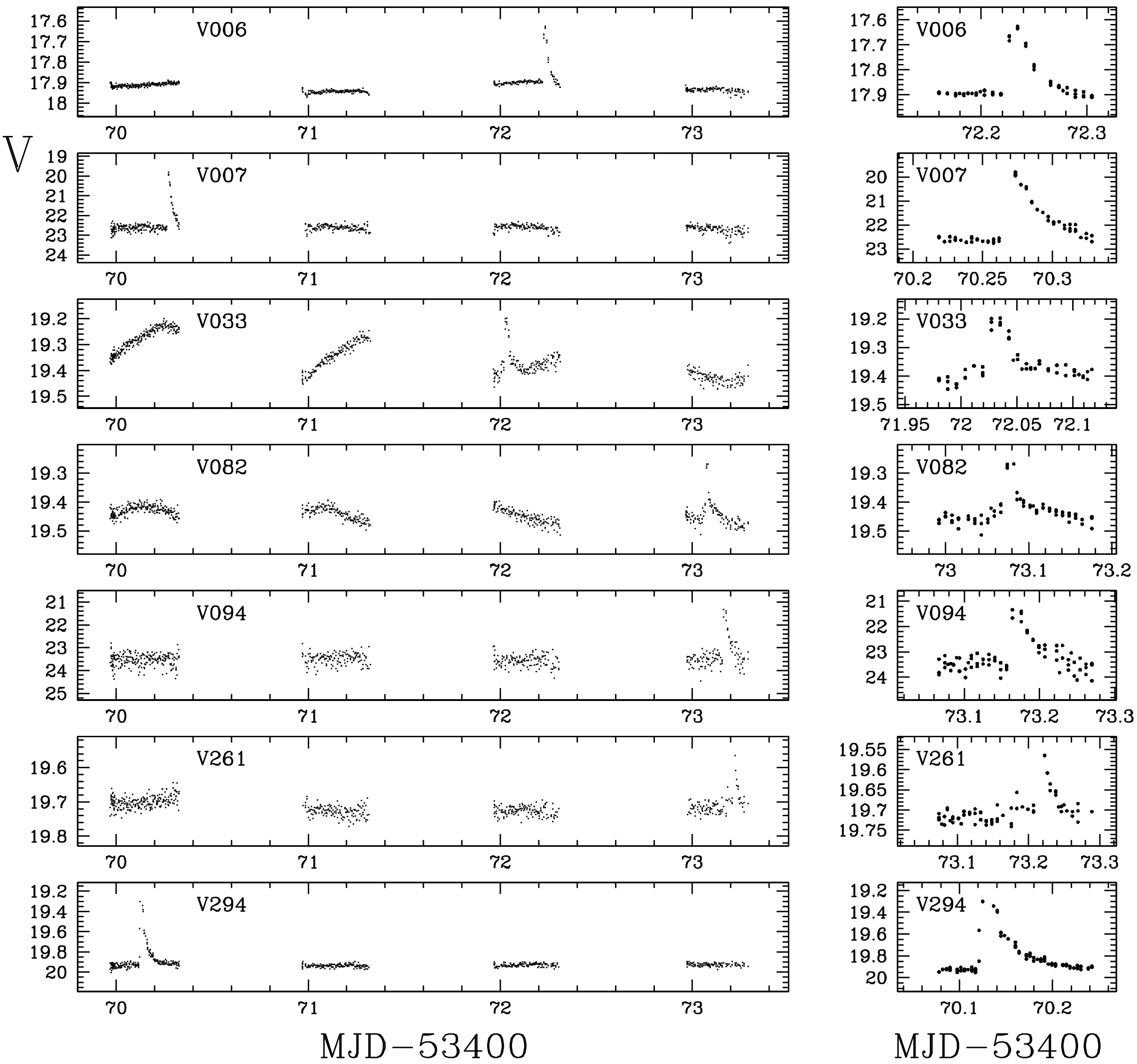

Fig. 15. Stars with flares. Note the the object V033 is also a periodic (very likely pulsating) variable with P = 1.1625 d for which phased light curve is illustrated in Fig. 12.

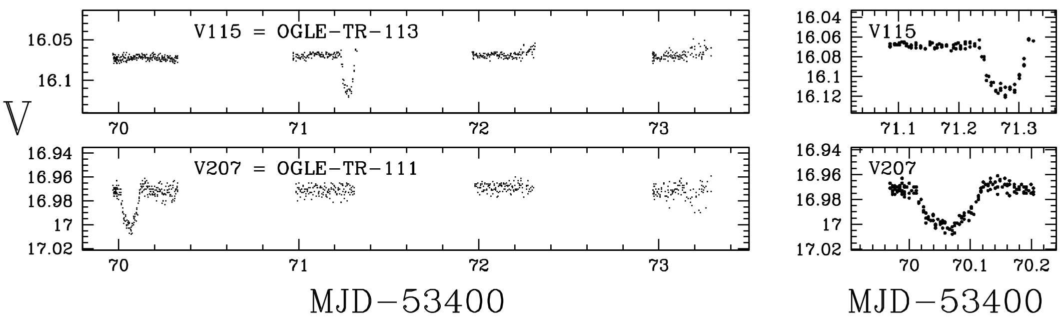

Fig. 16. Two planetary transits: V115 (OGLE-TR-113) and V207 (OGLE-TR-111).

ground-based wide-field variability surveys are powerful tools for drawing a more detailed picture of our Galaxy.

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