Stellar Variability Background in OGLE-I Microlensing Search

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ABSTRACT

We search OGLE-I photometric database for stars, which, as defined by formal criteria adopted by OGLE-I microlensing search, showed variability during only one out of 3 or 4 observing seasons. The results include 17 previously reported microlensing events, 2 newly discovered candidate events and 15 intrinsically variable stars that have a potential of contaminating samples of microlensing events. Based on photometry obtained in 1992 and 1993 OGLE #10 was tentatively included in the list of microlensing candidates, however its light curve in 1994 and 1995 shows many characteristics of the variable stars found in our search, and most likely it is not a microlensing event. For all stars which passed our tests, we provide 44×44 arcsec (101×101 pixels) centered subframes from each OGLE-I frame in I band. It is the first time when images used to derive photometry of microlensing events are available in convenient format to astronomical community.

Subject headings: Gravitational Microlensing – Photometry – Stars: Variables

1. Introduction

The search for rare cases of gravitational microlensing in the Local Group requires monitoring of $\sim 10^6$ stars over several months in order to yield a significant rate of detections. A common implementation adopted is to construct a massive photometry database and subsequently select stars which experienced brightening of the type we expect on theoretical grounds (see Paczyński, 1996, for a recent review of basic theory, current microlensing searches and results). For the vast majority of events the light curves should follow a single point mass microlensing curve. Possible departures and exceptions from this basic case are extremely interesting. For random distribution of stars the probability that a given star will be lensed twice over duration of the experiment is negligible. Large fraction of binary lenses is expected to give raise to the population of "wide binary" light curves with two separate amplification regions ($\sim 1\%$ of the total rate of events). However in most cases the secondary peak should be weak ($A_{\rm max} < 0.1$) and probably would only be discovered in light curves, which called attention because of the primary event (Di Stefano and Mao 1996). Photometry in very crowded fields, which are natural places to look for microlensing events, is often of limited quality. The majority of stars measured are just above the detection limit, many events have modest amplitudes, and numerous light curves are unevenly sampled. Therefore a microlensing curve may accidentally give a good fit to the brightening which is due to the intrinsic variability of the star. Certainly a repeated brightening of the same type would need to be very carefully examined before any claim of a detection of the wide binary microlensing repeater. As a result, it is generally hard to lower confusion rate without lowering the number of events returned by the procedure.

For microlensing events reported by OGLE-I project (Udalski et al. 1992) the basic requirement was that variability should occur during only one observing season (Udalski et al. 1994a). It was assumed that a sample of stars selected according to the above condition contains the majority of microlensing events and relatively few variable stars of other types. In this paper we investigate how many variable stars have light curves that, given the time sampling of OGLE-I experiment, appear constant during all seasons except for just one. The quantitative information about stellar variability background, against which microlensing events are detected, allows further tuning of the methods used in automated detection of the events.

2. Data

The data used in this paper is stored in OGLE-I database of measurements obtained during four observing seasons between 1992 and 1995. Only fields observed for 3 or 4 seasons were analyzed. The relevant part of the database consists of 20 fields: BW1-8, BWC, MM5-AB, MM7-AB (4 seasons of data) and BW9-11, MM1-AB, MM3, GB1 (no data in 1992). There were typically four months of observing time per season resulting in ~ 45 frames per field per season. All observations were made using 1-m Swope telescope at the Las Campanas Observatory operated by Carnegie Institution of Washington. A single Ford (Loral) 2048×2048 CCD was used with the pixel scale of 0.44 arcsec/pixel, covering 15×15 arcmin on the sky. Images in the database were de-biased and flat-fielded by an automated data pipe line based on IRAF "ccdred" routines. Photometry was performed using DoPhot package (Schechter, Mateo and Saha 1995). We refer to Udalski et. al (1992) for details of the photometric data pipeline and to Szymański and Udalski (1993) for a description of the database. After preliminary selection based on photometry alone, we also inspected actual images for 94 objects (see Section 3). From each good quality frame in I band OGLE-I database (grades A–E, F frames rejected), we extracted a 101×101 pix (44×44 arcsec) subframe centered on the star of interest. One of the main goals of this project is to provide such set of subframes for all stars which are described in our paper. This is the first data set of this type; actual frames used to derive photometry of microlensing events are available for a variety of studies, including independent photometry obtained with entirely different software (e.g. Alard and Lupton 1998). At the end of this article we provide an ftp address.

3. Search criteria

An estimate of the optical depth to microlensing requires full understanding of the selection effects. Udalski et al. (1994a) designed an automated selection procedure for microlensing events in order to facilitate calculation of the sensitivity function. A basic requirement for candidate stars was that they should vary during one observing season and stay constant during remaining seasons. Then more stringent conditions followed, i.e., a star should increase its brightness rather than decrease and a standard microlensing curve should yield a significant improvement of the fit with respect to a constant. Here we apply only the first group of conditions and we put no restrictions on variability type other than a genuine change in brightness during one of the observing seasons.

First we require at least 75 "good" photometric measurements in I band for stars observed during 3 seasons and 100 such measurements for stars with 4 seasons of data. This prevents many potential false alarms due to spurious stars which are inevitably detected by DoPhot, and does not noticeably affect the final sample, as the great majority of the objects are usually well measured. A "good" measurement comes from a frame of grade A–D (E, F rejected), has stellar DoPhot type and a standard deviation returned by DoPhot is less than 1.6 times median of DoPhot standard deviations for the entire set of measurements of this particular star.

A star is considered variable during a given season when:

1. At least 5 consecutive "good" points deviate consistently up or down from the average over "constant" seasons by more than $3\sigma_{\rm max}$, where $\sigma_{\rm max}$ is a function of the stellar magnitude and field (Udalski et al. 1993).

   or

2. There are at least 10 such points total.

A star is considered constant during remaining 2 or 3 seasons if:

1. There are at least 40 "good" measurements in I band after ± 4 "raw" σ rejection.

2. Dispersion of the "good" measurements is less than $\sigma_{\max}$ for a star of a given magnitude in a given field.

3. The star's mean magnitude from all "good" photometric points is $I < 19.5$.

Stars fainter than $V = 19.0$ were also tested for presence of close companions, as in this case seeing variations introduce large uncertainties in their photometry. The minimum allowed distance for the nearest star was a linear function of its magnitude. We used empirical formula of Udalski et al. (1993): $R_{crit} = 0.875 \times (21.0 - I)$ pixels.

The above criteria were programmed and filters were run on the I band light curves from OGLE-I database. Typically 60 stars per field were selected, ~ 1200 stars total out of $\sim 2 \times 10^6$. There are two previously reported microlensing events which did not pass this test. We discuss those exceptions in the next section.

Despite our efforts, it proved impossible to check reality of the recorded magnitude variations for stars which passed the test without visual inspection of the images. This is due to relatively large variety of CCD defects that were present in various parts of the frame and also bleeding columns whose impact on a particular star changes from frame to frame. We also could not afford extracting relevant pixels from each of the OGLE-I frames for 1200 stars. Therefore, we inspected light curves of the selected objects by eye and rejected the ones which showed purely erratic changes. Some of the stars had light variations correlated in time and position in the frames, a clear indication of a problem, usually bleeding column. Such objects were also removed. We left 94 objects, "promising" ones and also some material for case studies of the anticipated sources of spurious variability. For those stars we extracted a 101×101 pixels subframe from each frame in the OGLE-I database. These subframes were then checked for any possible factors which may have affected the photometry. Typical bad measurements were caused by physical CCD defects or bleeding columns. In some cases seeing variations in extremely crowded environment influence photometry despite good statistics. We found that of all object in the OGLE-I database which passed the above tests, 35 experienced a real change in brightness (OGLE #2a and #2b counted as two).

4. Results

4.1. Microlensing events

As we start the search with a subset of the conditions used by OGLE-I experiment to extract microlensing candidates, we should, in principle, recover all events previously found in the automated search by Udalski et al. (1994a). We do indeed find all events used for the estimate of the optical depth to microlensing in the direction of the Galactic Bulge. All remaining events reported by OGLE-I so far were detected in real time by the Early Warning System (hereafter EWS; Udalski et al. 1994b), except for OGLE #8, which was found by non-algorithmic means in some preliminary analysis of the BW9 field, but could not be included in the optical depth calculation. Observations of BW9 field started in 1993 and at the time Udalski et al. (1994a) published their results the data for only one observing season were available. It turns out that OGLE #8 is blended with a relatively bright star, close enough not to satisfy the condition for acceptable blends (Section 3). Moreover OGLE #19 due to its large amplitude was caught by the EWS, although it is fainter than $I = 19.5$. For completeness we include those two events in the final data set.

OGLE #13 is the first event detected on-line by MACHO collaboration (Alcock et al. 1994) that was followed up by the OGLE group (Szymański et al. 1994). It is located in GB5 field, which we do not analyze here. OGLE #10, most likely a variable star, is discussed in the next section.

Two of the newly discovered objects have light curves which are best interpreted as magnification due to microlensing. These are new OGLE-I microlensing candidates, OGLE #20 and OGLE #21. They were missed in the automated search by Udalski et al. (1994a), who had to compromise the number of detected events in order to eliminate human judgment.

In Table 1 we summarize basic information on OGLE-I microlensing events: identification numbers in I and V databases for a given field, position, source magnitude in unlensed state I_s, $V - I$ color, fitted maximum amplification $A_{\rm max}$, time scale t_0 (in days) and moment of the maximum light $t_{\rm max}$ (Heliocentric JD $-$ 2448000). Please note that t_0 used here is the time it takes the source to move by one Einstein radius in the sky relative to the lensing mass, while MACHO group is using duration of the event, $2t_0$. We assume no blending, i.e., that the amplified source accounts for 100% of the light measured within the PSF long before and long after the event. The observed shift of light centroid as the lensed star brightens (Goldberg and Woźniak 1998) and estimates based on artificial frames by Goldberg (1998) suggest that a fraction of strongly blended events should be large. The standard fit is irrelevant in case of OGLE #7 – a binary event (Udalski et al. 1994c).

Figure 1 shows full light curves along with the corresponding fit from Table 1. 30×30 arcsec finding charts are shown in Figure 4. A microlensed star is always at the center, as indicated by a white cross, north is up and east is to the left. Table 3 may be used to identify stars in the database of V measurements. A number starting with "N" indicates that the object was not detected in the template image and its photometry is stored in the database of the so called "new" objects (Szymański and Udalski 1993).

4.2. Variable stars

We found 15 variables which were formally constant during all seasons except for one. Full light curves are presented in Figure 2. It is quite surprising that most of them seem to show some regularities, taking into account that the set of conditions described in Section 3 strongly discriminates against periodicity. To quantify this first impression, we looked for periods between 0.1 and 100 days in those light curves using the Analysis of Variance method and following the approach of Udalski et al. (1994d). Table 2 contains results of this analysis. For all 15 stars we list: identification number in I database for a given field, position, mean I magnitude and mean $V - I$ color from the entire set of "good" measurements along with the amplitude ΔI. We detected periodicity in light curves of 12 stars (top portion of Table 2). For those objects we give the detected period P (in days) and the moment of the maximum brightness T_0 (JD Hel. $-$ 2448000) chosen to fall into the observing season, in which the star was found to be variable. Figure 3 shows corresponding phased light curves. An even more unexpected result is that four of the stars which passed the test were already found by the OGLE team in searches for strictly periodic variables ! (Udalski et al. 1995a, 1995b, 1996, 1997). The last column of Table 2 contains previous OGLE identifications, where appropriate. We do not attempt any further analysis of these objects and confine ourselves to the statement that they closely resemble miscellaneous variables described in detail by Olech (1996), majority of which probably have spotted surfaces.

The last 3 stars in Table 2 have no significant period in the range 0.1–100 days. Stars BW10 I 179313 and BW10 I 184744 may still have very long periods, while MM3 I 58214 went through a single outburst. In this case T_0 is the moment of the maximum measured brightness, while P is the time interval between T_0 and the moment when the star reached half of its maximum brightness. Finding charts for all objects from Table 2 are given in Figure 4.

OGLE #10 was tentatively reported as a candidate microlensing event by Udalski et al. (1994a). It came out of the automated procedure and at the time of discovery the data showed brightening during 1992 observing season and flat light curve during season of 1993. Nevertheless in 1994 and 1995 the star developed semi regular variations with the period around 36 days superimposed on overall brightening with a much longer time scale. The first feature is characteristic for variability of the majority of the stars classified as miscellaneous in the OGLE-I catalog (Olech 1996), and the second is reminiscent of the star BW10 I 179313. Therefore most likely OGLE #10 is a variable star similar to the ones analyzed by Olech (1996), of which quite many examples we find in our search.

5. Concluding remarks.

A general conclusion is that variability background in OGLE-I search was reasonably well separated from microlensing events, although OGLE #10, a single candidate which most likely is not a microlensing event, constitutes a 5% confusion rate. A variable star, just like any other star, may be amplified by microlensing, but an increase of brightness by 0.1 mag may be naturally explained by intrinsic variability of this star, especially that similar objects (certainly not microlensing events) apparently exist.

We find two additional possible events that were not returned by the automated procedure of Udalski et al. (1994a). This is not surprising since we relax some of the selection cuts applied before. Moreover, one of those events happened near the end of the observing season while the other had very short time scale and poorly sampled light curve. Both of them are very inconspicuous.

The outburst experienced by MM3 I 58214 (most likely a flare or CV star) is an important case which has a potential of contaminating samples of microlensing candidates. Suppose we had no data just before the flare. With photometric accuracy comparable to OGLE-I data such variable could be taken for a fading microlensing event and uncertainty would have to be resolved by spectroscopy and/or monitoring of the star long after the event.

We note a relatively large number of periodic or almost periodic variables which change amplitude. They mimic constant stars for time long enough to pass the most important criterion of the OGLE-I search, i.e., that a star should vary within a limited time interval with essentially constant flux at all other times. It is mostly due to relatively poor time coverage of the OGLE-I experiment and should not be difficult to overcome in the second phase of the project, OGLE-II (Udalski, Kubiak and Szymański 1997). Two recommendations can be made for the future. First, low amplitude events, e.g. with $A_{\max} < 1.5$, may be safely ignored in the calculation of the optical depth to prevent potential problems with objects similar to OGLE #10. MACHO team is already using such cut off to avoid contamination by "bumpers". Second, a requirement of roughly even photometric coverage of both sides of the magnification peak allows filtering out stars with (usually asymmetric) outbursts. OGLE-I events used in the optical depth determination satisfy such condition, however some of the events discovered by the EWS do not.

The full set of data used in this paper, including 101×101 pix subframes extracted from every I band image of each object in Tables 1 and 2, is available for public. Images in FITS format as well as photometric data in standard Johnson system may be retrieved via anonymous ftp from `astro.princeton.edu (128.112.24.45)` – directory `/ogle/var_background` and `sirius.astrouw.edu.pl (148.81.8.1)` – directory /ogle/var_background. See `README` file for details.

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Table 1. OGLE-I microlensing events.

Field	Star ID I	Star ID V	α_{2000}	δ_{2000}	I_s mag	$V-I$	$A_{\max}$	t_0 d	$t_{\max}$ [JD]*	OGLE #
BW7	117281	110374	18:04:24.80	-30:05:58.3	18.77	1.52	2.35	21.3	1154.2	1
BW5	178651	239408	18:02:52.08	-30:04:21.7	19.20	1.72	6.34	46.3	804.6	2a
BWC	10648	9055	18:02:52.02	-30:04:20.2	19.18	1.66	5.12	50.3	804.7	2b
BW3	161225	93508	18:04:43.45	-30:14:10.7	15.91	1.80	1.25	11.5	830.7	3
BW4	111538	N8860	18:04:16.27	-29:51:56.6	19.29	1.65	4.41	14.0	806.9	4
BWC	120698	97013	18:03:21.84	-30:02:32.0	18.01	1.55	7.36	13.3	824.3	5
MM5-B	128727	69133	17:47:45.19	-35:01:18.4	18.16	1.45	3.08	8.6	818.8	6
BW8	198503	189096	18:03:35.83	-29:42:00.8	17.53	1.80	...	...	...	7
BW9	138910	125157	18:00:49.20	-29:47:05.6	17.91	2.06	2.09	45.6	1218.1	8
MM7-A	86776	N22929	18:10:41.90	-25:50:33.9	19.22	1.69	1.93	16.6	814.7	9
BW6	167045	217426	18:03:45.13	-30:18:16.9	18.20	1.74	1.31	12.0	1537.4	11
BW5	83758	112206	18:02:24.62	-30:07:51.3	18.70	2.02	2.00	18.3	1582.6	12
MM1-A	123474	104845	18:06:48.67	-26:37:24.2	19.05	2.35	1.81	11.4	1822.1	14
BW3	142477	97949	18:04:37.26	-30:12:11.5	18.35	1.76	3.97	15.6	1853.1	15
BW5	72182	94317	18:02:07.60	-30:01:12.3	18.43	1.56	1.84	26.2	1884.9	16
BW10	176006	164907	18:00:56.60	-29:58:17.6	18.80	1.92	2.00	121.9	1999.2	17
BW1	67895	49873	18:02:11.10	-29:51:21.7	18.63	1.55	2.25	9.0	1918.1	18
MM3	3289	N90940	18:07:28.53	-29:11:30.9	19.77	1.15	6.62	5.0	1931.2	19
MM5-A	41271	N34210	17:46:57.68	-34:47:14.4	19.15	1.74	5.23	30.0	858.6	20
BW6	80736	104108	18:03:10.79	-30:15:34.2	18.81	1.92	2.02	5.1	1162.1	21

*Heliocentric JD − 2448000

Table 2. Variable Stars found in the search.

Field	Star ID I	Star ID V	α_{2000}	δ_{2000}	$\langle I \rangle$ mag	$V - I$	ΔI	P d	T_0 [JD]*	OGLE ID
BW2	205380	166732	18:02:48.18	-30:18:23.2	15.92	1.98	0.14	37.59	730.90	V28
BW3	127604	88469	18:04:36.95	-30:21:10.5	15.85	2.14	0.13	26.26	725.70	
BW3	161220	108232	18:04:46.43	-30:14:10.7	15.77	2.03	0.14	35.98	1824.82	#10
BW5	10705	13570	18:01:54.55	-30:03:21.1	14.68	1.99	0.11	79.76	1552.19	V10
BW9	160297	146622	18:00:59.81	-29:53:05.9	15.49	2.23	0.16	24.11	1830.25	V21
BW11	74701	64198	18:00:41.46	-30:18:27.4	15.84	2.21	0.18	24.88	1145.92	
MM1-B	198992	194344	18:07:08.19	-26:48:52.0	17.24	2.20	0.17	84.96	1823.35	
MM3	30724	31147	18:07:39.85	-29:10:38.3	16.95	2.19	0.18	19.35	1823.88	
MM3	89081	90520	18:07:41.33	-29:01:10.8	15.64	2.13	0.13	43.86	1531.39	
MM3	227272	236470	18:08:19.38	-28:57:25.9	15.70	1.84	0.15	15.72	1135.94	
MM5-A	17258	6871	17:46:51.07	-34:44:03.1	15.55	2.32	0.13	60.87	1547.82	V17
MM5-A	199110	89237	17:47:56.95	-34:51:34.7	14.23	1.99	0.19	33.96	1823.67	
BW10	184744	172256	18:01:08.64	-30:07:10.7	17.04	2.42	0.21	...	...	
BW10	179313	167019	18:00:55.29	-29:56:21.3	15.45	2.05	0.10	...	...	
MM3	58214	56998	18:07:33.83	-29:00:37.8	19.49	1.27	1.20	4.52	1176.82	

*Heliocentric JD − 2448000

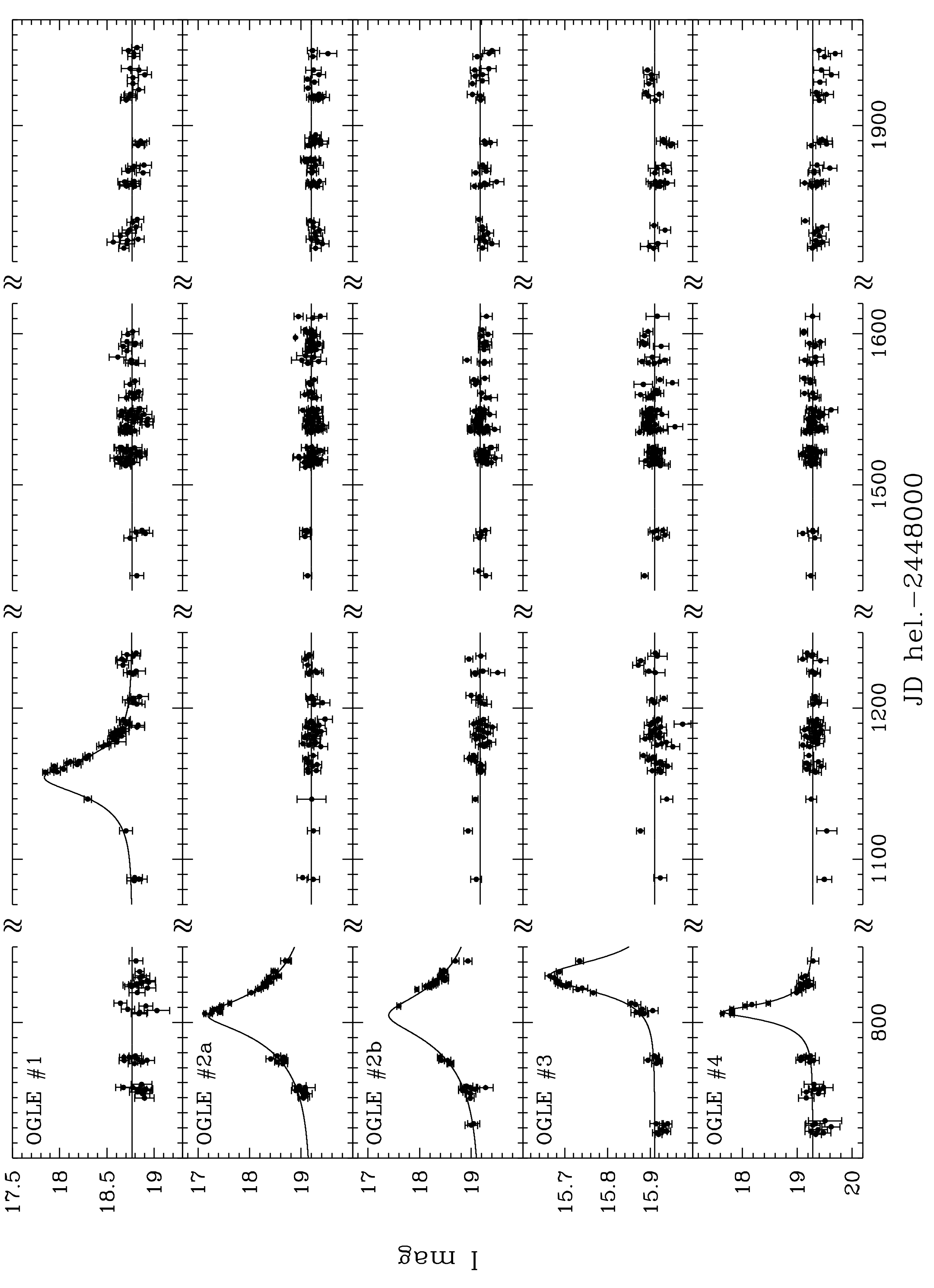

Fig. 1a.— OGLE-I microlensing events.

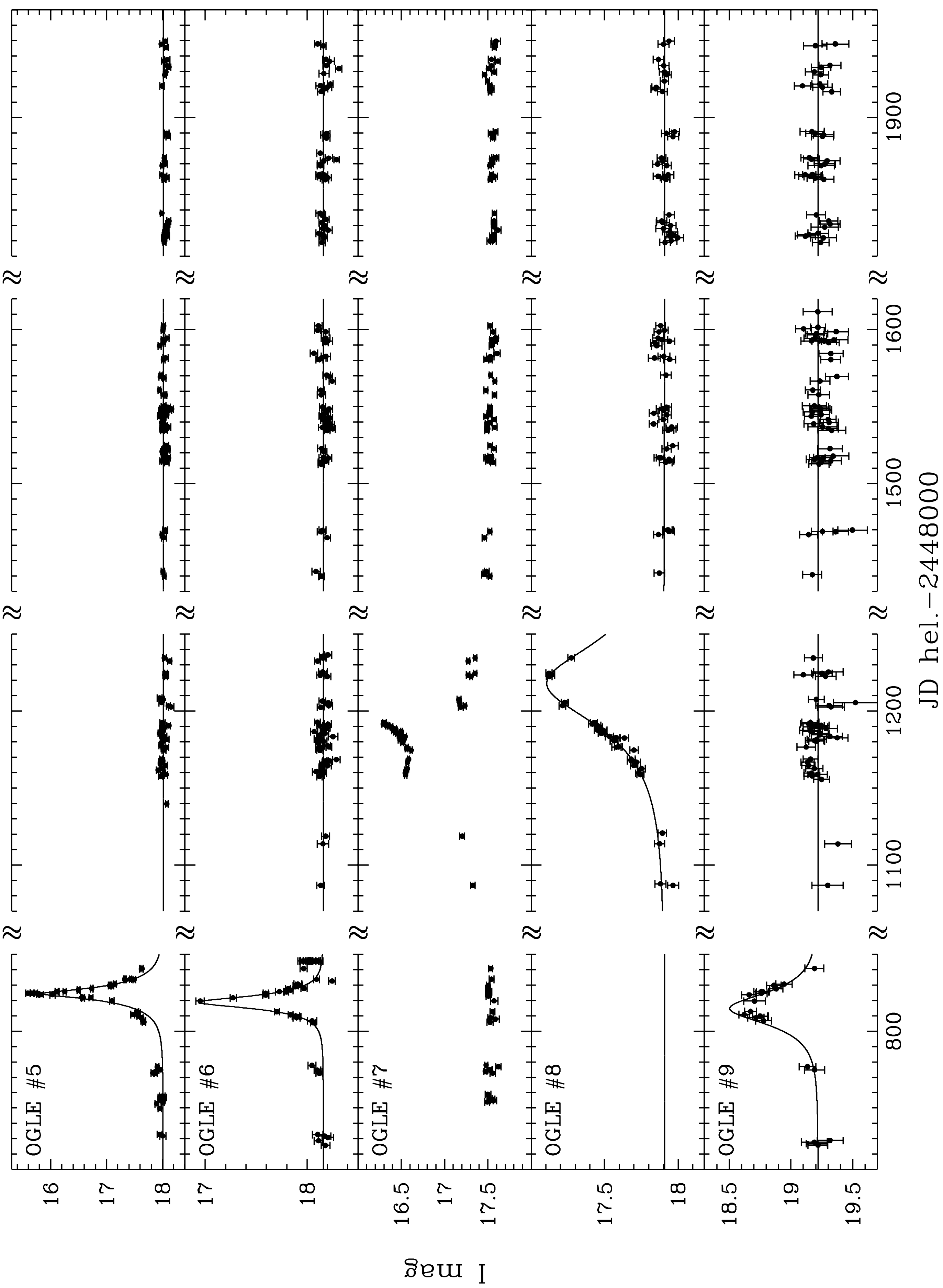

Fig. 1b.— OGLE-I microlensing events – continued.

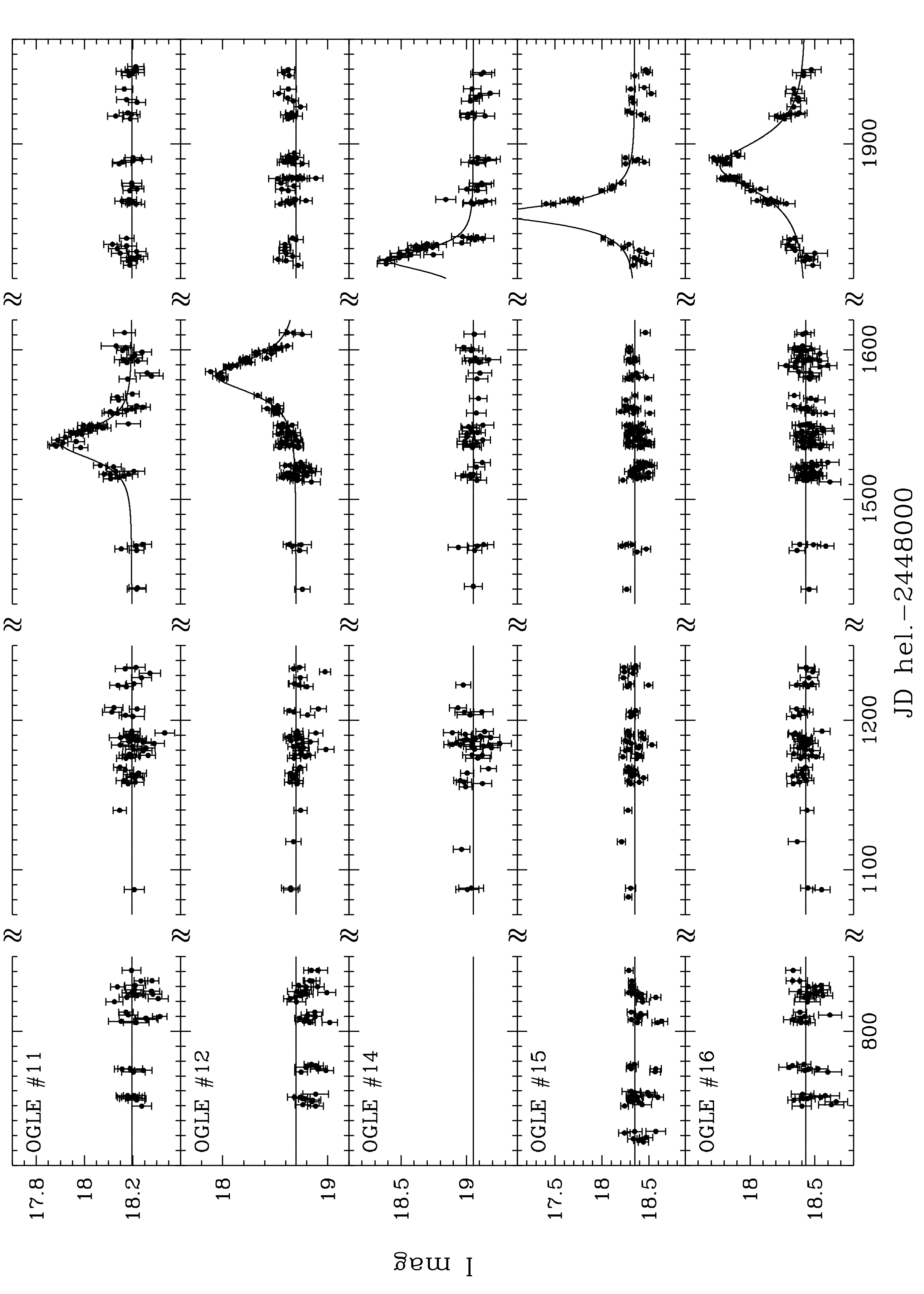

Fig. 1c.— OGLE-I microlensing events – continued.

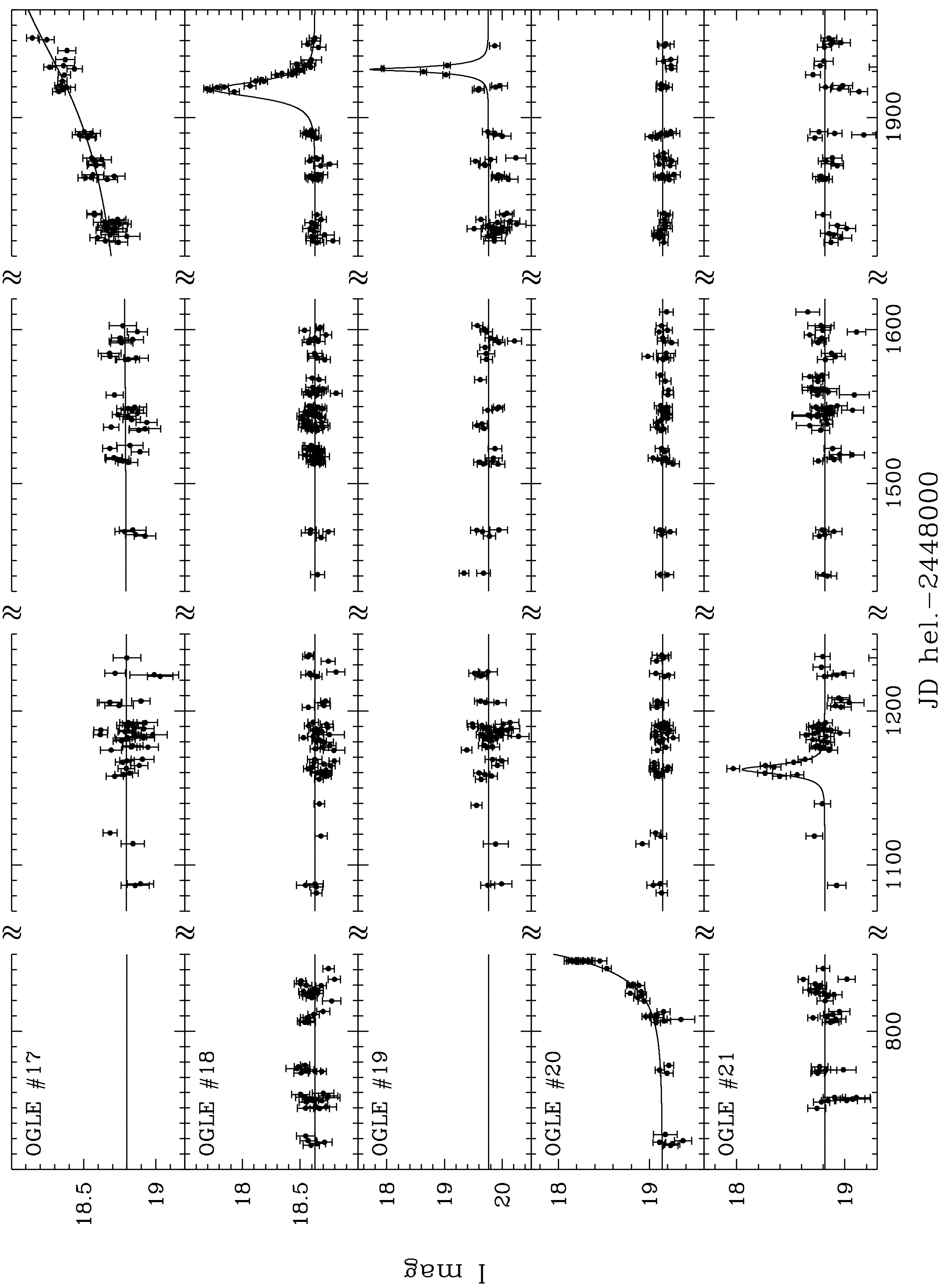

Fig. 1d.— OGLE-I microlensing events – continued.

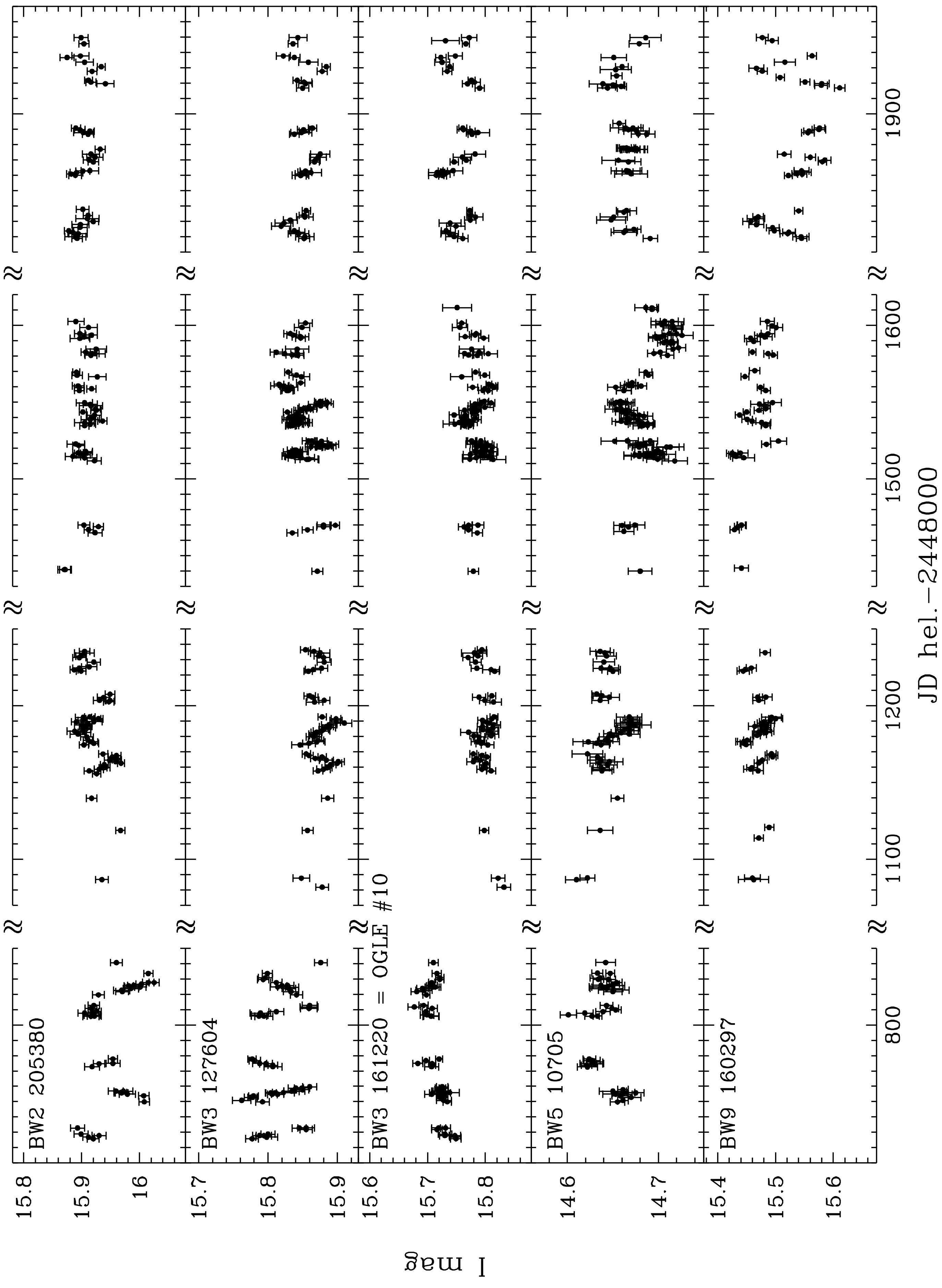

Fig. 2a.— Variable stars found in the search.

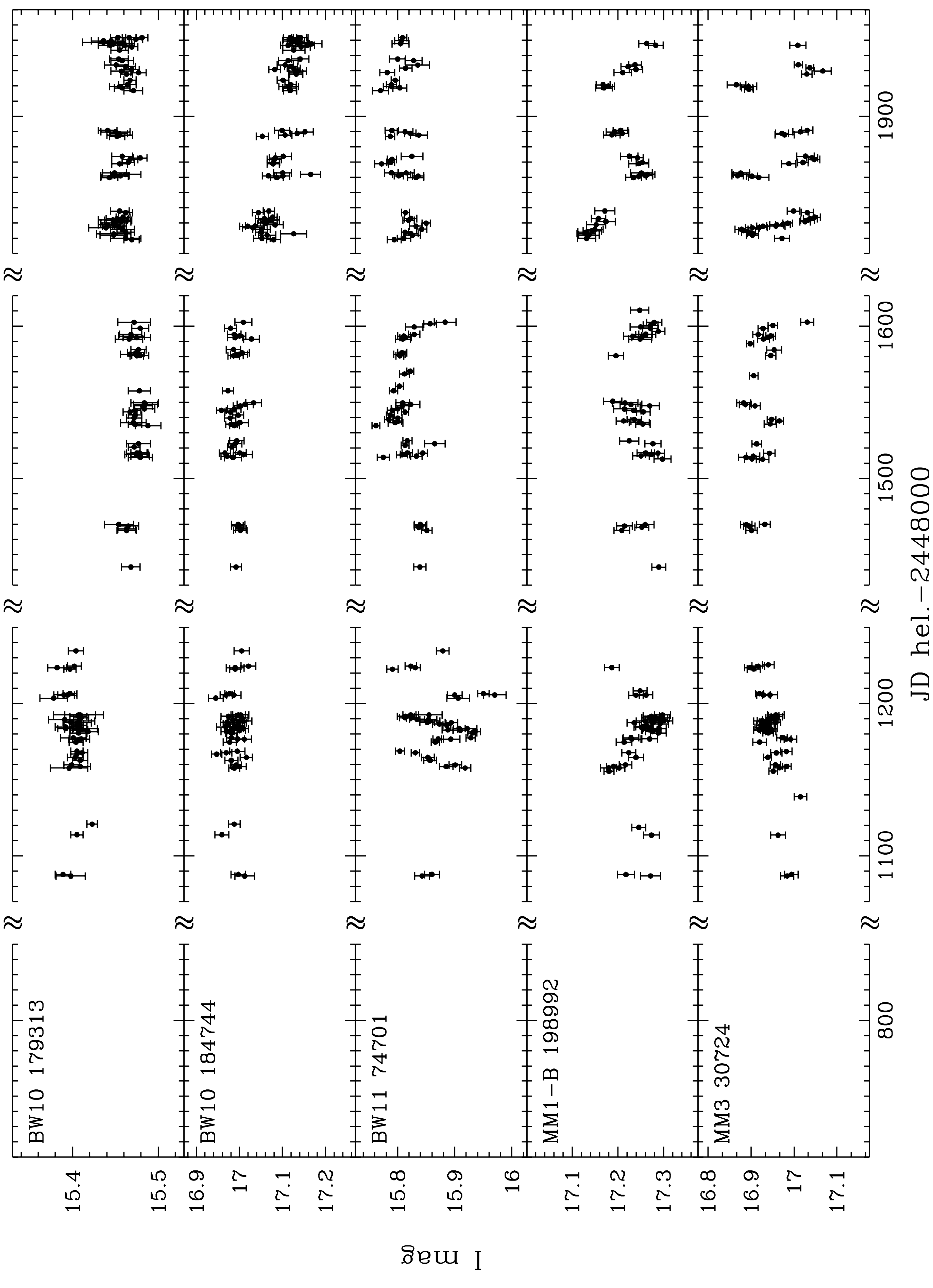

Fig. 2b.— Variable stars found in the search – continued.

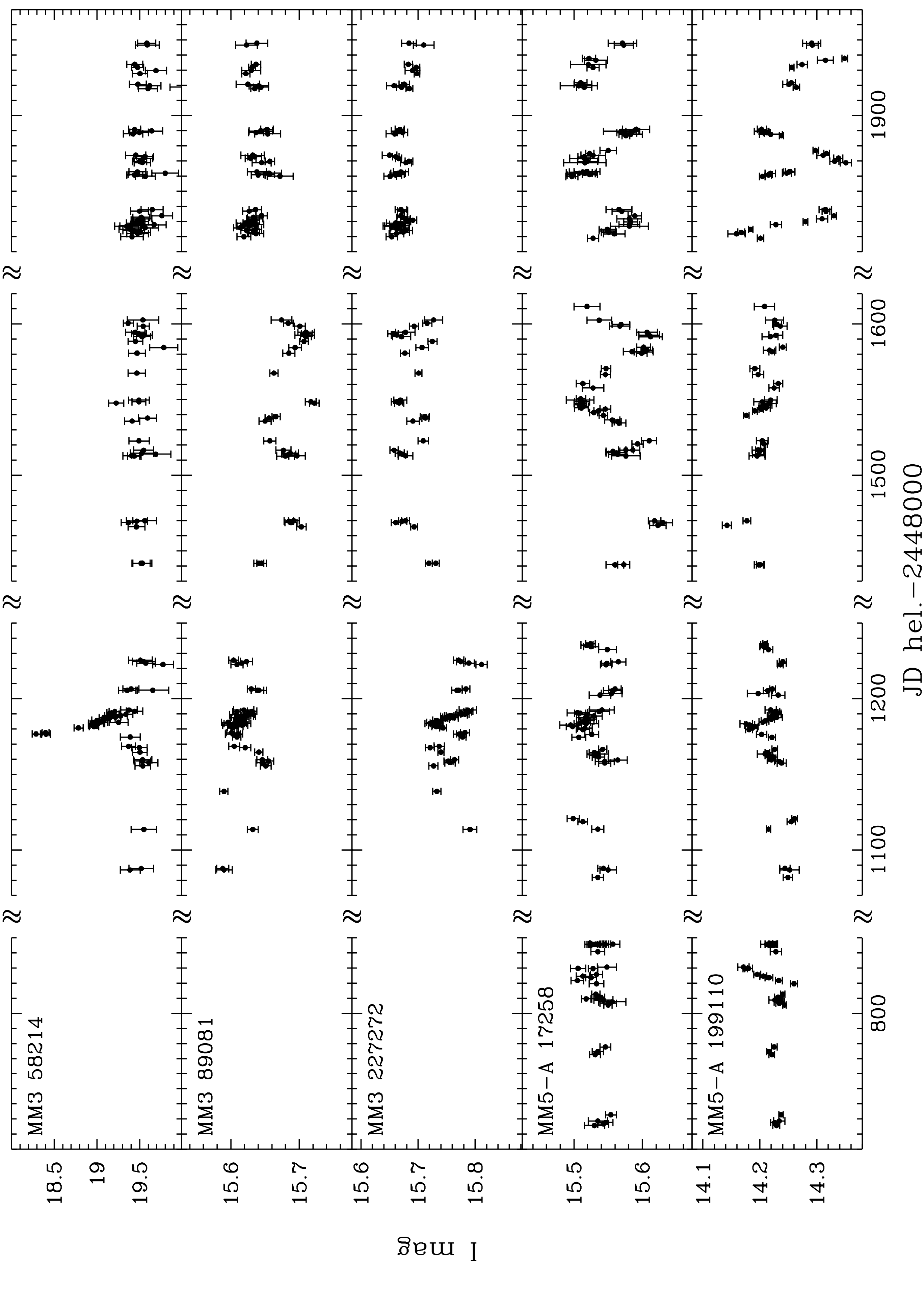

Fig. 2c.— Variable stars found in the search – continued.

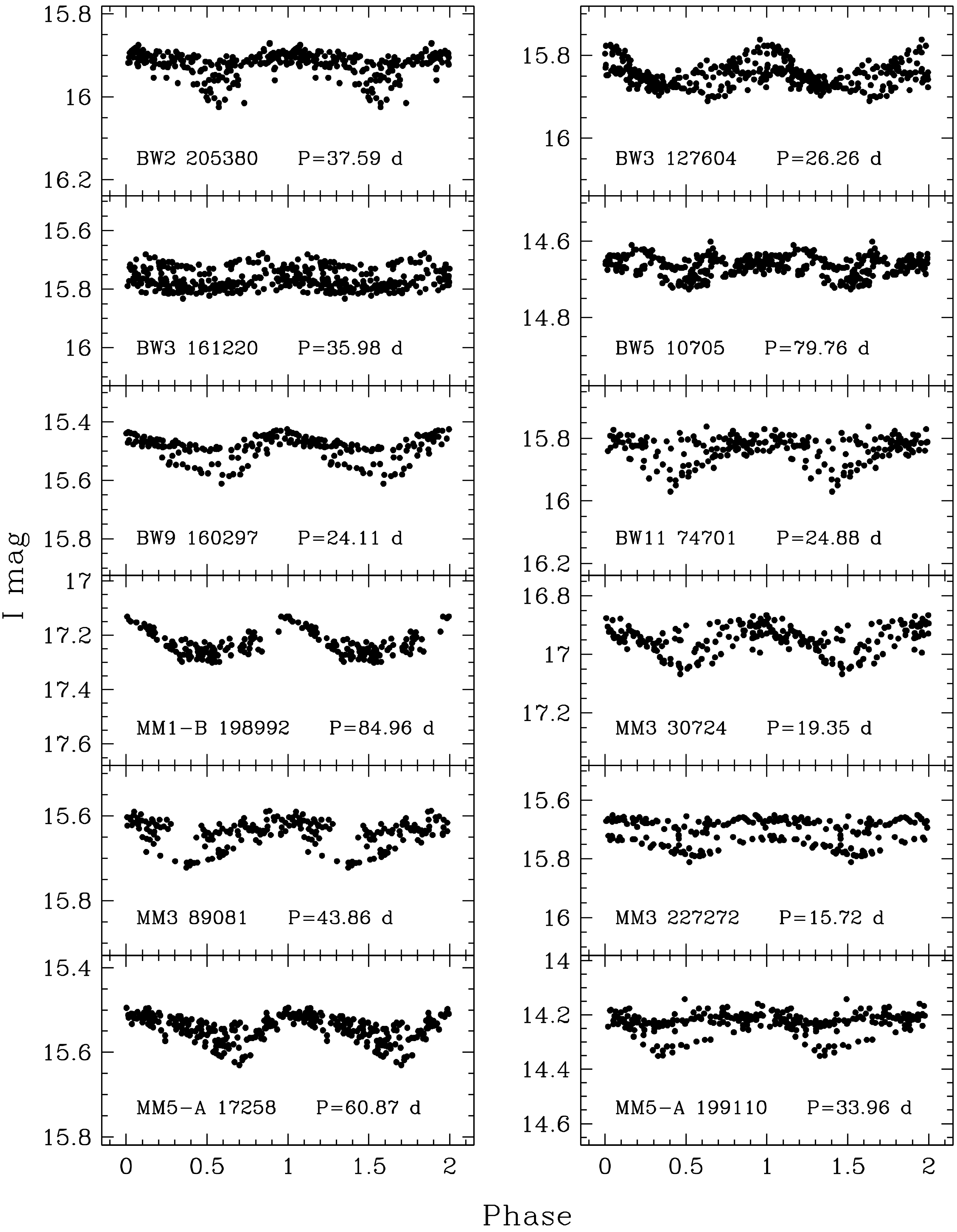

Fig. 3.— Results of the test for periodicity.

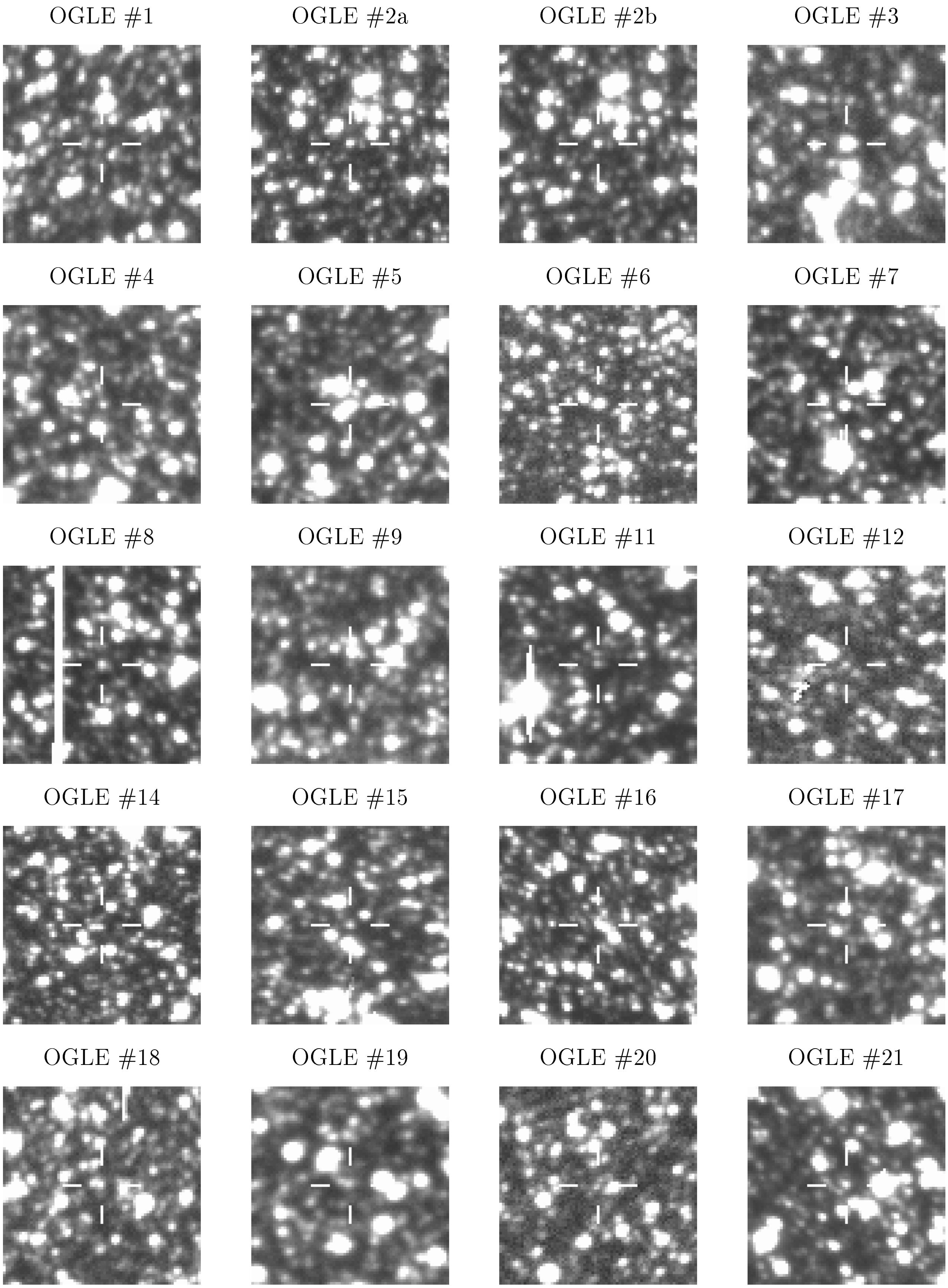

Fig. 4a.— Finding charts.

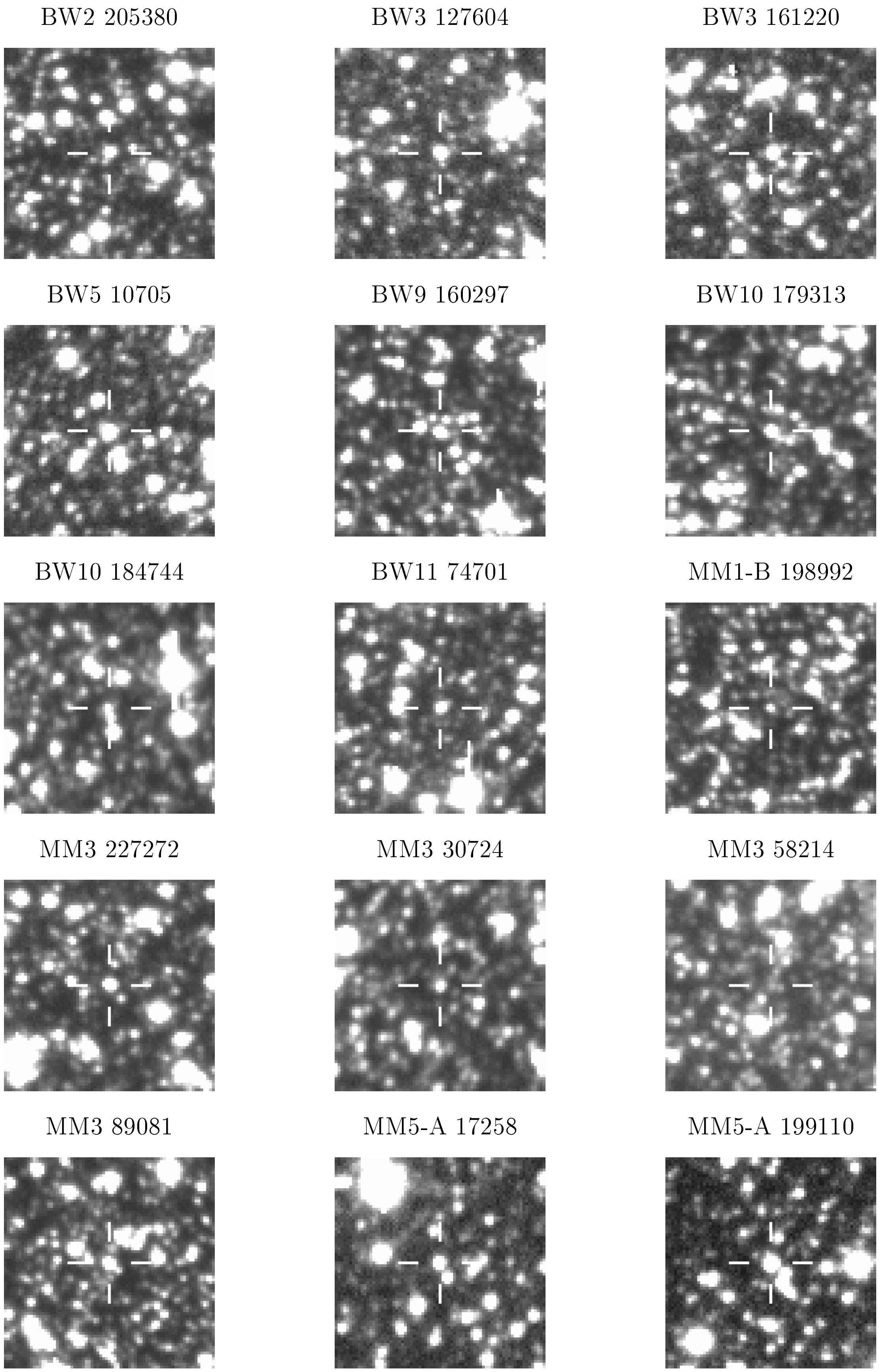

Fig. 4b.— Finding charts – continued.