The Optical Gravitational Lensing Experiment. Additional Planetary and Low-Luminosity Object Transits from the OGLE 2001 and 2002 Observational Campaigns*

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ABSTRACT

The photometric data collected by OGLE-III during the 2001 and 2002 observational campaigns aiming at detection of planetary or low-luminosity object transits were corrected for small scale systematic effects using the data pipeline by Kruszewski and Semeniuk and searched again for low amplitude transits. Sixteen new objects with small transiting companions, additional to previously found samples, were discovered. Most of them are small amplitude cases which remained undetected in the original data.

Several new objects seem to be very promising candidates for systems containing substellar objects: extrasolar planets or brown dwarfs. Those include OGLE-TR-122, OGLE-TR-125, OGLE-TR-130, OGLE-TR-131 and a few others. Those objects are particularly worth spectroscopic follow-up observations for radial velocity measurements and mass determination. With well known photometric orbit only a few RV measurements should allow to confirm their actual status.

All photometric data of presented objects are available to the astronomical community from the OGLE INTERNET archive.

1. Introduction

Extensive photometric campaigns conducted by the OGLE-III photometric survey in 2001 and 2002 (Udalski *et al.* 2002abc) proved that the transit photometric technique of detection of extrasolar planets can be successfully applied. The technique allows to identify an extrasolar planet or other small size object when the inclination of its orbit is close to 90°and the small body passes (transits) the disk of its host star every orbital revolution obscuring tiny part of its light. The drop of brightness during the transit – of the order of a few percent or less – and duration of transit provide information on the size of small companion. Unfortunately, the photometry alone does not allow to unambiguously distinguish

*Based on observations obtained with the 1.3 m Warsaw telescope at the Las Campanas Observatory of the Carnegie Institution of Washington.

between extrasolar planets and other astrophysical low-luminosity objects like brown dwarfs or very red M-type dwarfs, as all these bodies may have similar dimensions.

On the other hand when the transit method is combined with high accuracy radial velocity measurements the degeneracy can be removed as the mass of the above objects differs by two orders of magnitude or more. Moreover, in that case all the most important parameters of the planet or low-luminosity object like its mass, radius and density can be accurately derived because the inclination of orbit is known in the case when transits occur. Thus, the large scale photometric survey of large number of stars can potentially provide many candidates for extrasolar planetary systems. Then they must be spectroscopically followed up for the final confirmation with radial velocity techniques. It is worth noticing that because the photometric orbit of the candidates is well known the spectroscopic follow up requires much less observing time. Also, with the transit method the extrasolar planetary systems can be detected at much larger distances than with other methods because precise photometry may be obtained for relatively faint stars.

The search for planetary and low luminosity object transits became one of the top priority goals of the OGLE project after the beginning of the third phase – OGLE-III. During the first photometric campaign carried out in June/July 2001 three fields in the direction of the Galactic center were regularly observed. Results of the campaign were presented in Udalski *et al.* (2002a) and in a supplement (Udalski *et al.* 2002b), after reanalyzing the data with more efficient transit detection algorithm of Kovács, Zucker and Mazeh (2002). In total 59 objects (two turned out to be the same star observed in overlapping region of two fields) revealing small amplitude transits were discovered among about 52 000 disk stars from the nearby Galactic arm. For the vast majority of candidates more than two transits were observed allowing determination of photometric orbits. Based on the estimation of size and shape of the light curve (ellipsoidal variation) it was clear from the very beginning that most of the objects found may have rather stellar companions. However, in several cases all photometric characteristics indicated very good candidates for extrasolar planets or substellar companions.

The second OGLE-III transit campaign was conducted in February/May 2002. This time three fields located in the Carina part of the Galactic disk were monitored. Sixty two new objects with transiting companions were discovered in the Carina campaign data (Udalski *et al.* 2002c). Again, in several cases photometric data indicated substellar companions.

In the meanwhile, many groups followed up spectroscopically OGLE-III candidates. In January 2003 the first object, namely OGLE-TR-56, was confirmed by Konacki *et al.* (2003) as the first extrasolar planetary system discovered with the transit method. A few months later another object, OGLE-TR-3, was claimed by Dreizler *et al.* (2003) to be also a planetary system.

Detection of transits caused by planetary objects requires extremely high accuracy of photometric measurements. For instance, Jupiter would cause a transit only about 1% deep when observed from outside the solar system. This is one of the main reasons why the transit method has not been successfully applied until now. The smaller the transit depth, the bigger the chance that it is caused by a substellar object.

The OGLE-III photometric data are of high quality due to stable hardware and a new method of data reduction based on image subtraction techniques (Alard 2000, Woźniak 2000). For the brightest stars the standard deviation of the entire data set of 800–1100 observations is usually smaller than 5 milimagnitudes. Nevertheless, even visual inspection of the data indicates that some low level systematic effects can be present in the OGLE-III data. For instance, changing zenith angle of observed fields may produce systematic errors in photometry at milimagnitude levels due to differential refraction. As all kinds of systematic errors smear out the details in the folded light curves, it became clear that non-negligible number of, in particular low amplitude, transits could have been lost in the previous analyzes of the OGLE data.

Recently Kruszewski and Semeniuk (2003, in preparation) analyzed the OGLE-III data for systematic effects. They prepared a data pipeline that learns about the magnitude of the most significant systematic errors based on several hundreds best photometry stars and then corrects photometry of all stars for those systematic effects.

In this paper we present results of the repeated search for transits in the OGLE-III photometric data from 2001 and 2002 campaigns corrected for systematic effects with the Kruszewski and Semeniuk (2003, in preparation) data pipeline. As we expected, we discovered additional 16 objects with transiting companions lost in the noise in our previous analyzes. Several of our new candidates reveal transits of very small amplitude indicating Jupiter-size companions. They are very good candidates for transiting extrasolar planets. Similarly to our previous transit samples the photometric data of our new candidates are available to the astronomical community from the OGLE INTERNET archive.

2. Observational Data

All observations presented in this paper were collected with the 1.3-m Warsaw telescope at the Las Campanas Observatory, Chile (operated by the Carnegie Institution of Washington), during the third phase of the OGLE project. The telescope was equipped with a wide field CCD mosaic camera consisting of eight 2048×4096 pixel SITe ST002A detectors. The pixel size of each detector is 15 μm giving the 0.26 arcsec/pixel scale at the focus of the Warsaw telescope. Full field of view of the camera is about $35' \times 35'$. The gain of each chip is adjusted to be about 1.3 e^-/ADU with the readout noise of about 6 to 9 e^-, depending on chip.

The 2001 OGLE transit campaign lasted from June 12 to July 28, 2001. More than 800 epochs of three fields in the direction of the Galactic center were collected on 32 nights. The exposure time was set to 120 seconds, and all fields were observed every 12 minutes. The photometric data of the 2002 campaign were collected during 76 nights spanning 95 days starting from February 17,

2002. Three fields located in the Carina region of the Galactic disk were observed continuously with the time resolution of about 15 minutes. In total, more than 1100 epoch were collected for each field. The exposure time was 180 second in that case. All observations were collected with the *I*-band filter. For more details on the observing strategy, observed fields and photometry techniques the reader is referred to the original papers on the 2001 (Udalski *et al.* 2002a) and 2002 campaigns (Udalski *et al.* 2002c).

The photometric data from the original transit campaigns were additionally supplemented with random epoch photometric observations collected to the end of May 2003. The number of additional observations reached 300 in the case of the 2001 campaign data and several or several tens in the case of 2002 campaign data.

3. Correction for Systematic Effects and Transit Search

All stars with accurate enough photometry (standard deviation of all observations not larger than 0.015 mag) that were used for transit search in the previous papers (about 52 000 and 103 000 for 2001 and 2002 campaigns, respectively) were subject to the procedure of removing effects of small systematic errors in the data. The data pipeline was written by Kruszewski and Semeniuk (2003, in preparation) and will be described in detail in a separate paper. In short, the software corrects the data for effects of differential refraction, and small drifts of the magnitude scale and its zero point. Based on several hundreds best constant stars selected for each field, it calculates the magnitude of the systematic effects. Then all stars from the sample are corrected for these effects.

In the next step, corrected photometry of all stars was searched for transits similar to the original papers. We again used the fast and efficient BLS algorithm of Kovács, Zucker and Mazeh (2002). We used the same parameters of the BLS algorithm as in the 2001 and 2002 campaigns (Udalski *et al.* 2002b) and limited our search for transits to periods from 1.05 to 10 days.

In the final step the light curves of all candidates were inspected visually. We removed from our list of transit candidates all object already presented in Udalski *et al.* (2002abc) and suspected objects found during earlier analyzes. We discovered many new objects, usually with very small amplitudes which were not detected previously. However, on the final list of additional transit objects only those that have a significant probability of being a true transit were left. Therefore we removed a large number of new detections that were evidently grazing eclipses (small amplitude V-shape of eclipses) or clear blends of an eclipsing system with a star.

4. Discussion

Sixteen objects with transiting planetary or low-luminosity companions remained on our list of new candidates found in the 2001 and 2002 OGLE-III photometry. Table 1 presents all basic data on these objects. The notation of objects follows that used by OGLE for previous transit campaigns. Therefore the first object in Table 1 is designated as OGLE-TR-122.

T a b l e 1

New OGLE-III planetary and low luminosity object transits

Name	RA (J2000)	DEC (J2000)	P [days]	T_0 -2452000	I [mag]	ΔI [mag]	$N_{\rm tr}$
OGLE-TR-122	$11^{\rm h}06^{\rm m}51\overset{\rm s}{.}99$	$-60°51'45\overset{''}{.}7$	7.26867	342.28258	15.61	0.019	5
OGLE-TR-123	$11^{\rm h}06^{\rm m}51\overset{\rm s}{.}19$	$-61°11'10\overset{''}{.}1$	1.80380	324.97937	15.40	0.008	12
OGLE-TR-124	$10^{\rm h}59^{\rm m}49\overset{\rm s}{.}57$	$-61°52'07\overset{''}{.}5$	2.75330	327.35782	15.10	0.011	5
OGLE-TR-125	$10^{\rm h}57^{\rm m}51\overset{\rm s}{.}95$	$-61°43'58\overset{''}{.}3$	5.30382	343.82550	15.82	0.013	4
OGLE-TR-126	$10^{\rm h}59^{\rm m}42\overset{\rm s}{.}01$	$-61°32'34\overset{''}{.}2$	5.11080	327.40830	15.57	0.022	3
OGLE-TR-127	$10^{\rm h}55^{\rm m}10\overset{\rm s}{.}25$	$-61°31'04\overset{''}{.}9$	1.92720	329.84698	14.97	0.011	8
OGLE-TR-128	$10^{\rm h}54^{\rm m}27\overset{\rm s}{.}54$	$-61°38'17\overset{''}{.}3$	7.39100	327.42530	15.00	0.016	5
OGLE-TR-129	$10^{\rm h}50^{\rm m}51\overset{\rm s}{.}12$	$-61°34'55\overset{''}{.}2$	5.74073	327.36759	16.19	0.034	3
OGLE-TR-130	$10^{\rm h}51^{\rm m}23\overset{\rm s}{.}54$	$-61°47'22\overset{''}{.}0$	4.83037	327.28057	15.94	0.028	5
OGLE-TR-131	$10^{\rm h}50^{\rm m}04\overset{\rm s}{.}86$	$-61°51'32\overset{''}{.}5$	1.86990	324.94513	15.69	0.011	9
OGLE-TR-132	$10^{\rm h}50^{\rm m}34\overset{\rm s}{.}72$	$-61°57'25\overset{''}{.}9$	1.68965	324.70067	15.72	0.011	11
OGLE-TR-133	$17^{\rm h}49^{\rm m}51\overset{\rm s}{.}32$	$-29°56'20\overset{''}{.}4$	5.31075	83.34913	16.63	0.034	3
OGLE-TR-134	$17^{\rm h}52^{\rm m}29\overset{\rm s}{.}95$	$-29°33'01\overset{''}{.}7$	4.53720	79.91817	13.49	0.011	2
OGLE-TR-135	$17^{\rm h}52^{\rm m}24\overset{\rm s}{.}27$	$-29°39'22\overset{''}{.}4$	2.57330	79.83362	15.16	0.019	5
OGLE-TR-136	$17^{\rm h}54^{\rm m}59\overset{\rm s}{.}23$	$-29°19'39\overset{''}{.}1$	3.11580	76.10417	14.93	0.016	7
OGLE-TR-137	$17^{\rm h}56^{\rm m}12\overset{\rm s}{.}65$	$-29°45'03\overset{''}{.}1$	2.53782	75.64246	15.85	0.030	7

In the subsequent columns of Table 2 the following data are provided: Identification, equatorial coordinates (J2000), orbital period, epoch of mid-eclipse, I-band magnitude outside transit, the depth of transit, and number of transits observed ($N_{\rm tr}$). Accuracy of the magnitude scale is about 0.1–0.2 mag. In Appendix the light curves with close-ups around the transit and finding charts of all objects from Table 1 are presented. The finding chart is a $60'' \times 60''$ subframe of the I-band reference image centered on the star. The star is marked by a white cross. North is up and East to the left in these images.

The observed transits can be caused by extrasolar planets or brown dwarfs or small late M-type dwarfs. Radial velocity measurements are necessary to distinguish between these possibilities. It is worth noticing that the new objects usually show small transit depth. Therefore, the new sample includes several objects that belong to the best OGLE-III candidates for extrasolar planetary systems.

However, one should remember that blending of a regular eclipsing star with

Table 2

Dimensions of stars and companions for central passage ($i=90°$)
and amplitudes of $\cos P$ and $\cos 2P$ variability.

Name	R_s $[R_\odot]$	R_c $[R_\odot]$	M_s $[M_\odot]$	a_{c1} mmag	a_{c2} mmag
OGLE-TR-122	0.72	0.086	0.66	$0.43(-2.31\pm1)$	$0.40(-0.84\pm1)$
OGLE-TR-123	2.56	0.205	3.24	$0.40(+0.42\pm1)$	$0.39(+4.52\pm1)$
OGLE-TR-124	0.52	0.047	0.44	$0.29(+0.39\pm1)$	$0.27(+0.30\pm1)$
OGLE-TR-125	1.42	0.142	1.56	$0.50(-0.11\pm1)$	$0.47(+0.31\pm1)$
OGLE-TR-126	1.06	0.138	1.08	$0.35(-1.56\pm1)$	$0.33(+1.07\pm1)$
OGLE-TR-127	0.74	0.066	0.68	$0.34(-0.07\pm1)$	$0.33(+0.45\pm1)$
OGLE-TR-128	5.06	0.556	7.58	$0.51(+0.42\pm1)$	$0.48(+2.97\pm1)$
OGLE-TR-129	0.68	0.108	0.61	$0.57(-0.78\pm1)$	$0.49(+0.78\pm1)$
OGLE-TR-130	0.30	0.042	0.22	$0.43(+0.83\pm1)$	$0.40(-0.61\pm1)$
OGLE-TR-131	0.65	0.059	0.59	$0.43(+1.11\pm1)$	$0.41(+2.02\pm1)$
OGLE-TR-132	1.05	0.094	1.06	$0.34(+2.26\pm1)$	$0.33(+1.49\pm1)$
OGLE-TR-133	0.50	0.081	0.42	$0.66(+1.52\pm1)$	$0.67(-0.95\pm1)$
OGLE-TR-134	1.15	0.103	1.19	$0.58(-0.42\pm1)$	$0.58(-0.41\pm1)$
OGLE-TR-135	2.72	0.327	3.50	$0.67(+1.73\pm1)$	$0.63(+5.43\pm1)$
OGLE-TR-136	1.88	0.207	2.20	$0.60(+0.87\pm1)$	$0.54(+1.10\pm1)$
OGLE-TR-137	1.05	0.157	1.06	$0.74(+1.73\pm1)$	$0.66(+2.34\pm1)$

total eclipses and a close optical or physically related (wide binary system) unresolved in the seeing disk neighbor can produce a light curve mimicking transits. Therefore some of our new candidates can actually be faked transits caused by blending effect. Probability of blending is much higher in the 2001 campaign data because of strong stellar background by the Galactic bulge stars. The blending problem should also be clarified by high resolution spectroscopy.

In Table 2 we present estimation of the size of transiting objects in our new candidates and host stars calculated in similar way to the previous papers (Udalski *et al.* 2002abc). Unfortunately, without any additional information on the radius of the primary it is not possible to obtain actual size of the companion when the errors of individual observations are comparable to the transit depth. Due to well known degeneracy between radii of the host star and companion, R_s and R_c, inclination i, and limb darkening u, similar quality photometric solutions can be obtained for different inclinations of the orbit and radii of components (in the I-band the transit light curve is practically insensitive to the limb darkening parameter u) making selection of the proper solution practically impossible.

Because the radius of the primary cannot be presently constrained as we do not know spectral types of primary stars, and their colors can be affected to unknown degree by the interstellar extinction only the lower limit on the size of the companion can be calculated assuming that the transit is central, *i.e.*, $i=90°$. The corresponding radius of the primary is also the lower limit.

In Table 2 we list dimensions of the primary and low-luminosity companion assuming additionally that the host star follows the mass-radius relation for main sequence stars ($R/\mathrm{R}_\odot = (M/\mathrm{M}_\odot)^{0.8}$). The mass of the primary is also listed in Table 2. In practice the transits might be non-central, *i.e.*, the size of the star and companion can be larger than given in Table 2. Also when the host star is evolved the estimations can be inaccurate. Solid line in the close-up windows in Appendix shows the transit model light curve calculated for the central passage. In some cases the fit is not satisfactory indicating the inclination smaller than 90°. However, in most cases the central passage fit is practically indistinguishable from others so at this stage it is impossible to derive other values than the lower limits of radii provided in Table 2.

In the last two columns of Table 2 we list the amplitudes and errors of the periodic sinusoidal variation with period P (a_{c1}) and $2P$ (a_{c2}) fitted to the photometric data. Periodicity P is interpreted as an reflection effect while $2P$ as an ellipsoidal effect. Presence of the latter at statistically significant level immediately indicates stellar companion or a blend of eclipsing system with nearby star (Drake 2003, Sirko and Paczyński 2003). The amplitudes are provided in the same form as in Sirko and Paczyński (2003): $b_i(a_{ci}/b_i\pm1)$ where a_{ci} is the amplitude and b_i its error. In this way one can immediately see the ratio of amplitude to its error, *i.e.*, significance of the effect.

Transits in a few newly discovered objects are certainly caused by stellar companions. The light curve of such systems exhibits clearly a statistically significant ellipsoidal effect (*e.g.*, OGLE-TR-123, OGLE-TR-128, OGLE-TR-135) what indicates that the companion mass is relatively large. In the case of OGLE-TR-128 perhaps even hints of a secondary eclipse are seen in the light curve. Also our limits on size of companions from Table 2 suggest evidently stellar companions in all these cases. The remaining objects do not show statistically significant ellipsoidal variation or reflection effect.

On the other hand, there is a group of several objects where the transiting companions can be much smaller and those stars are very good candidates for extrasolar planetary systems. In particular, the objects from the Carina region of the Galactic disk, namely OGLE-TR-122, OGLE-TR-125, OGLE-TR-127, OGLE-TR-129, OGLE-TR-130, or OGLE-TR-131 belong to the most promising, from the photometric point of view, candidates for planetary systems. This group of stars is particularly worth spectroscopic follow up observations as the chance that the companions are substellar objects is larger than in other cases. It is worth noting that additional transits of OGLE-TR-122 and OGLE-TR-125 were observed in 2003 season. Therefore the photometric ephemerides of these two objects are much more accurate than of others. The new detections from 2001 campaign from the Galactic center are less promising for extrasolar planet discoveries. Only OGLE-TR-133 and OGLE-TR-134 and perhaps OGLE-TR-137 may host substellar companions. The latter object might, however, display a weak ellipsoidal variation.

Results of our new search for transits in the corrected OGLE-III data indicate that careful analysis of the systematic errors significantly improves quality of photometry. Sixteen new detections increase the number of OGLE objects with transiting companions by 13%. However, most of the new objects reveal low depth transits and therefore are very good candidates for extrasolar planetary systems. Therefore, we plan to run the Kruszewski and Semeniuk (2003, in preparation) algorithm also on our other photometric data, namely collected during 2003 transit campaigns.

The photometric data of all new objects with transiting companions discovered in the OGLE-III 2001 and 2002 photometric data corrected for systematic effects are available in the electronic form from the OGLE archive:

http://ogle.astrouw.edu.pl

ftp://ftp.astrouw.edu.pl/ogle/ogle3/transits/new_2001_2002

or its US mirror

http://bulge.princeton.edu/~ogle

ftp://bulge.princeton.edu/ogle/ogle3/transits/new_2001_2002

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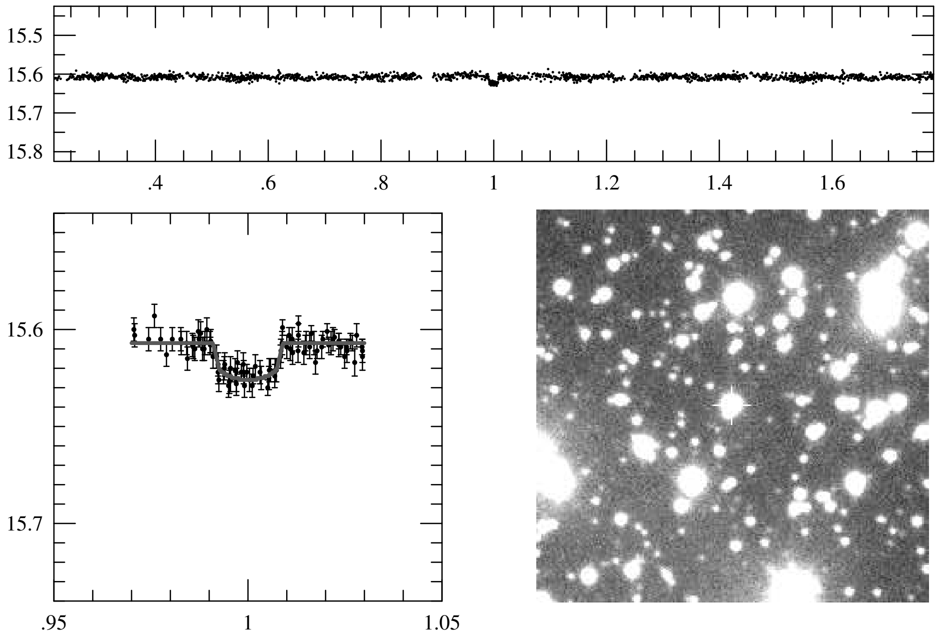
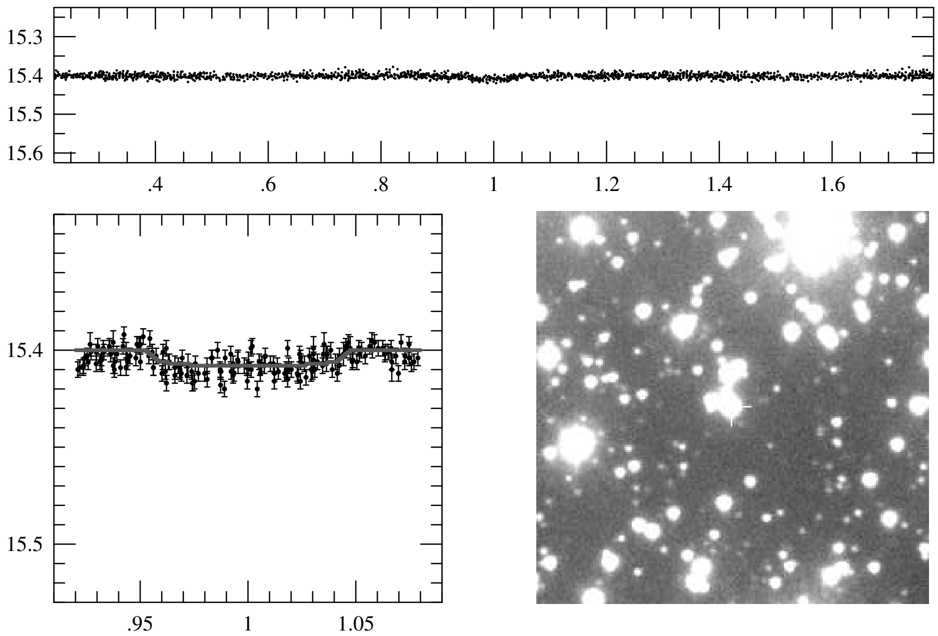
Appendix

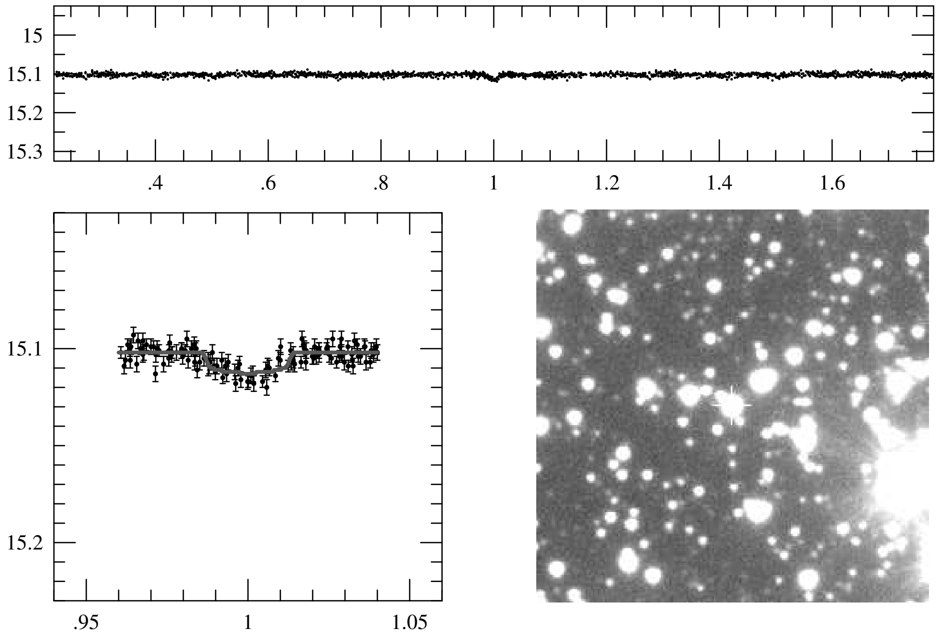
OGLE-TR-122 P=7.26867 (days)



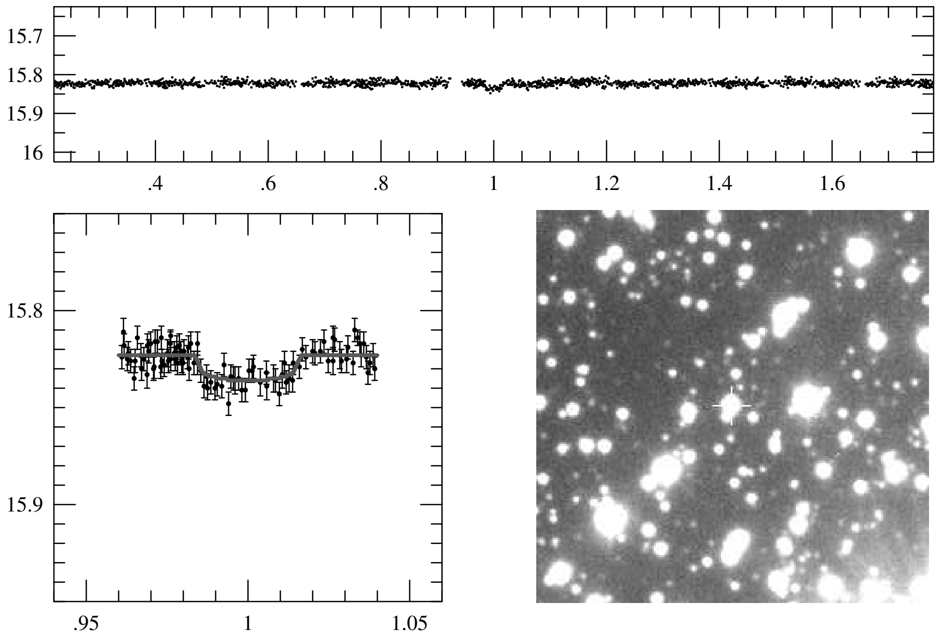
OGLE-TR-123 P=1.80380 (days)



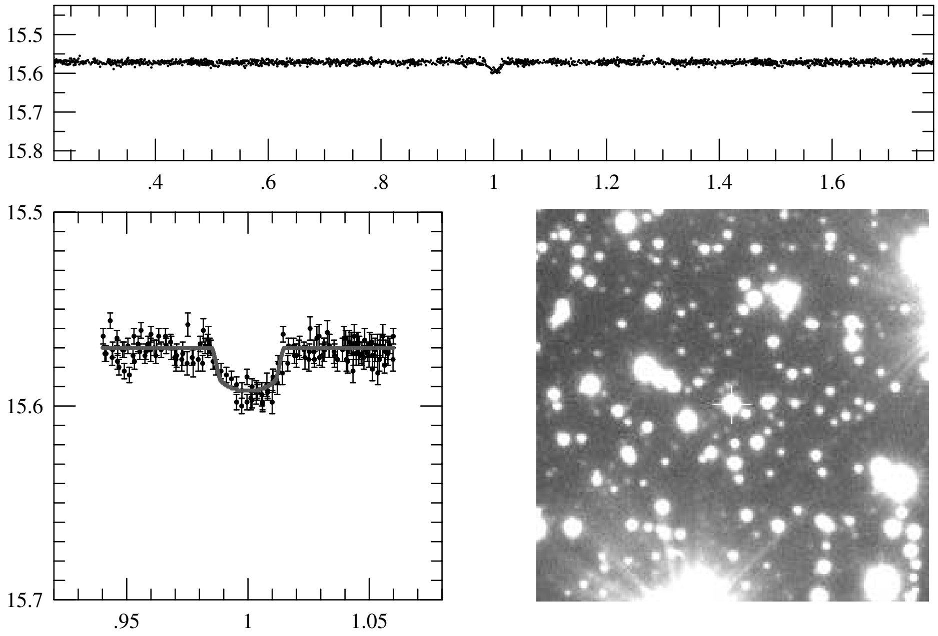
OGLE-TR-124 P=2.75330 (days)



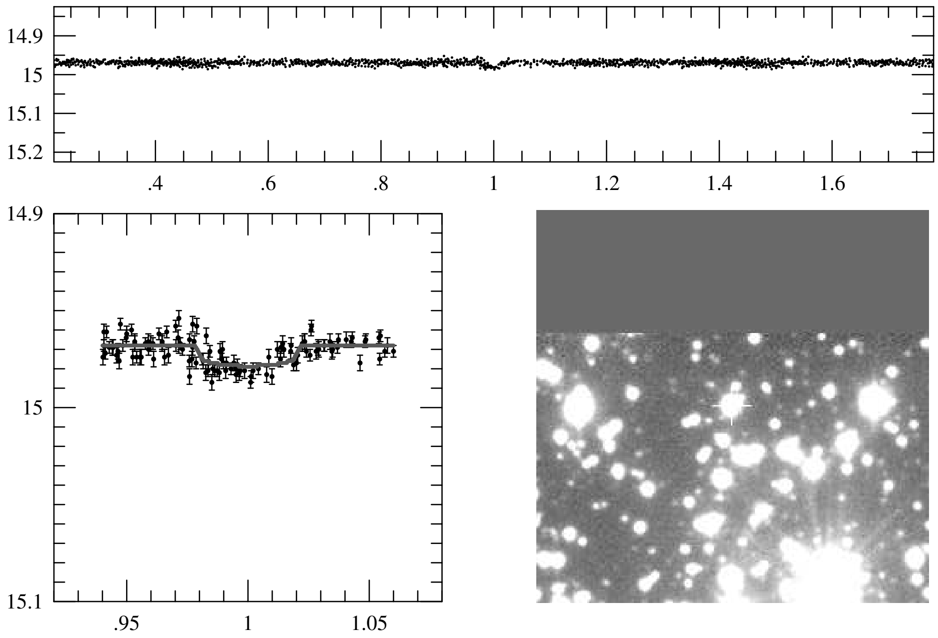
OGLE-TR-125 P=5.30382 (days)



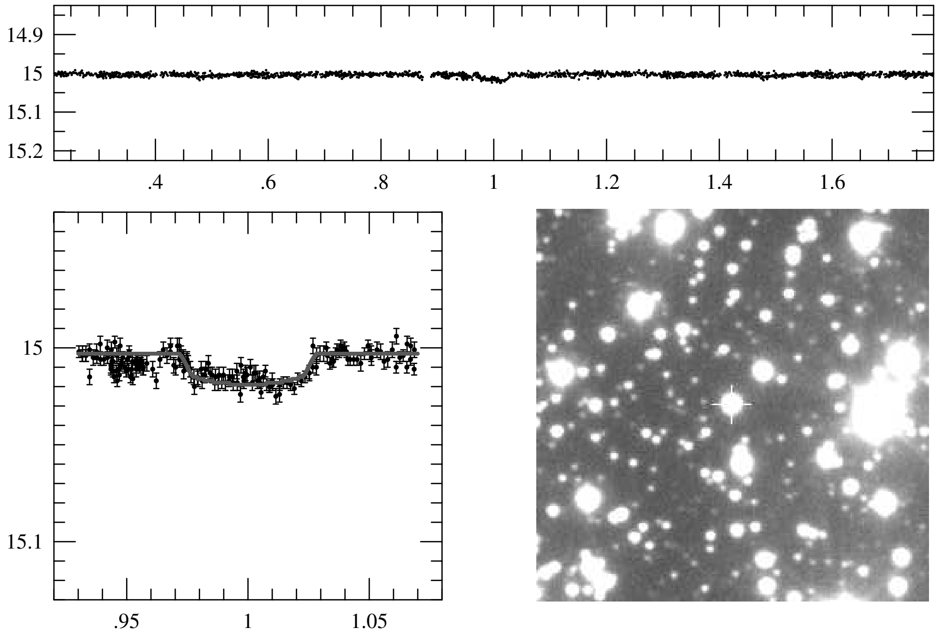
OGLE-TR-126 P=5.11080 (days)



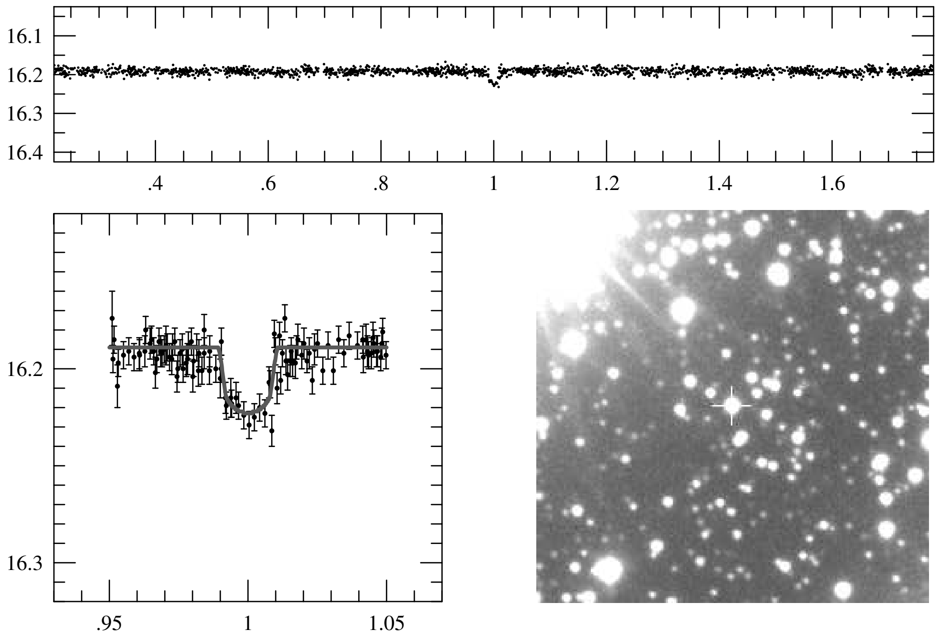
OGLE-TR-127 P=1.92720 (days)



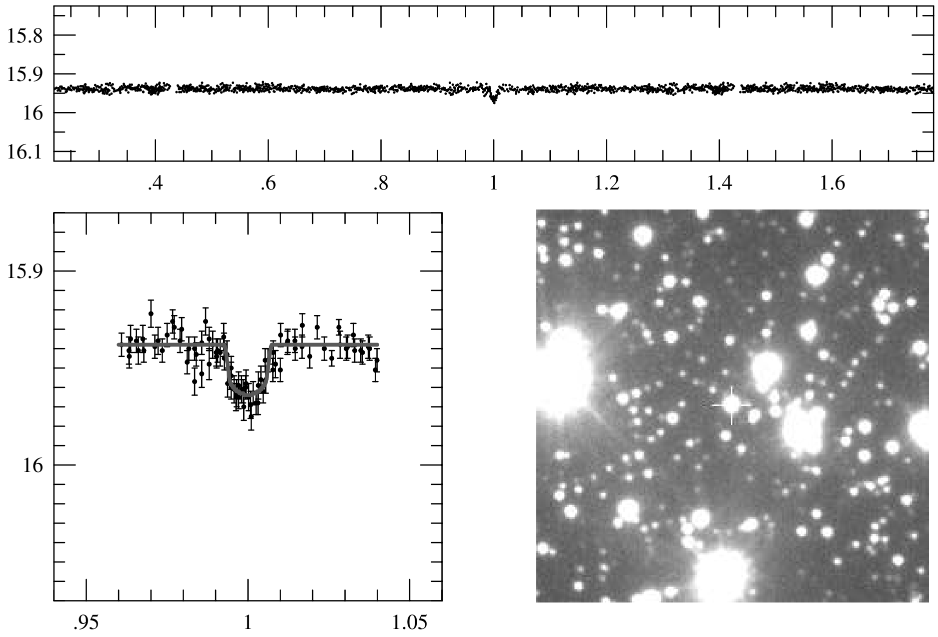
OGLE-TR-128 P=7.39100 (days)



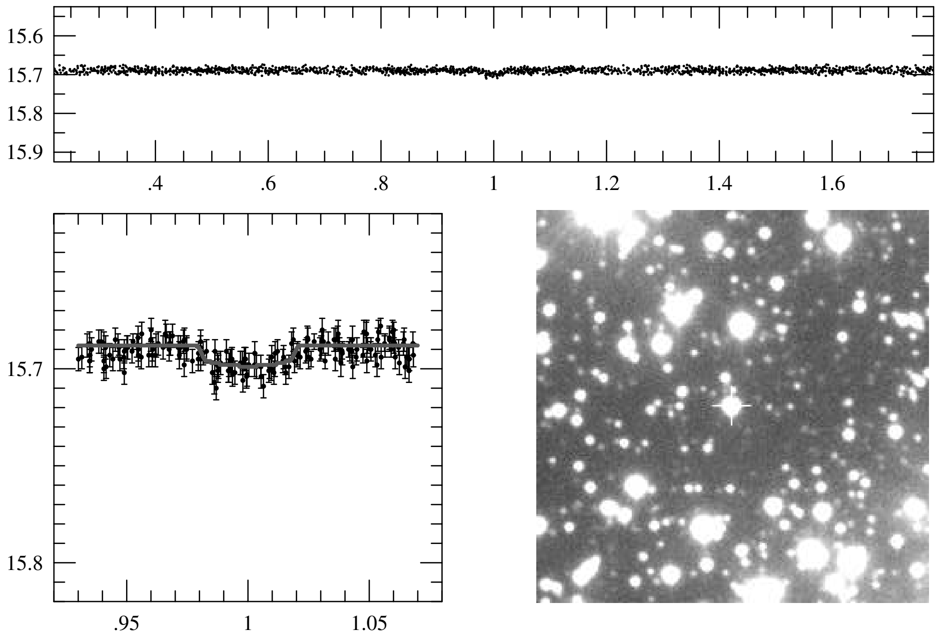
OGLE-TR-129 P=5.74073 (days)



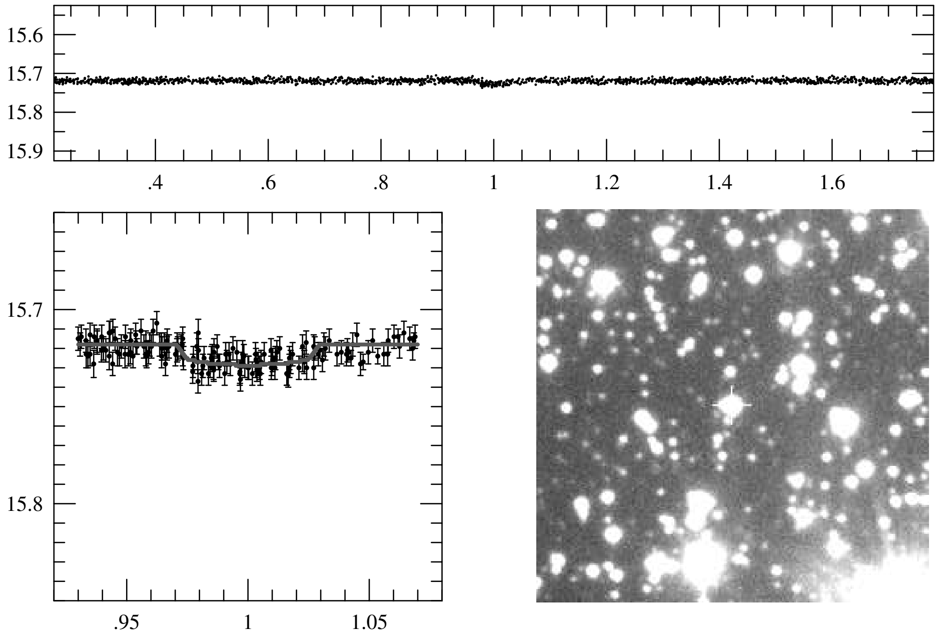
OGLE-TR-130 P=4.83037 (days)



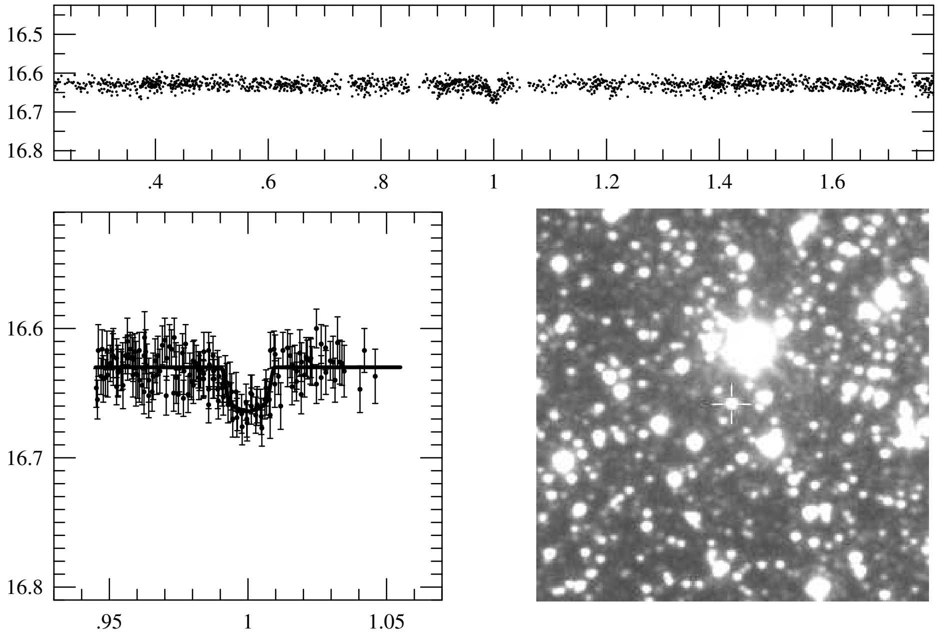
OGLE-TR-131 P=1.86990 (days)



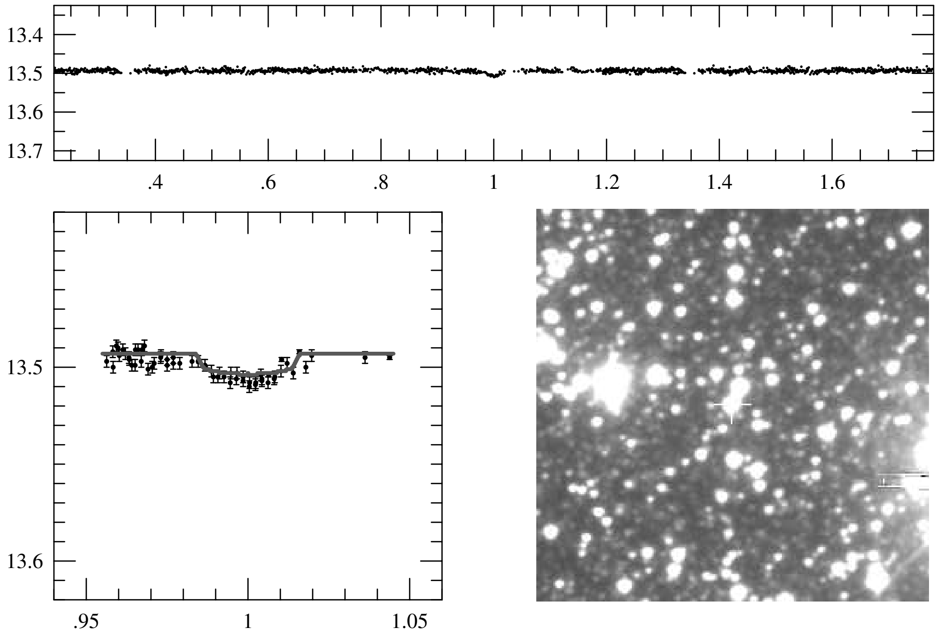
OGLE-TR-132 P=1.68965 (days)



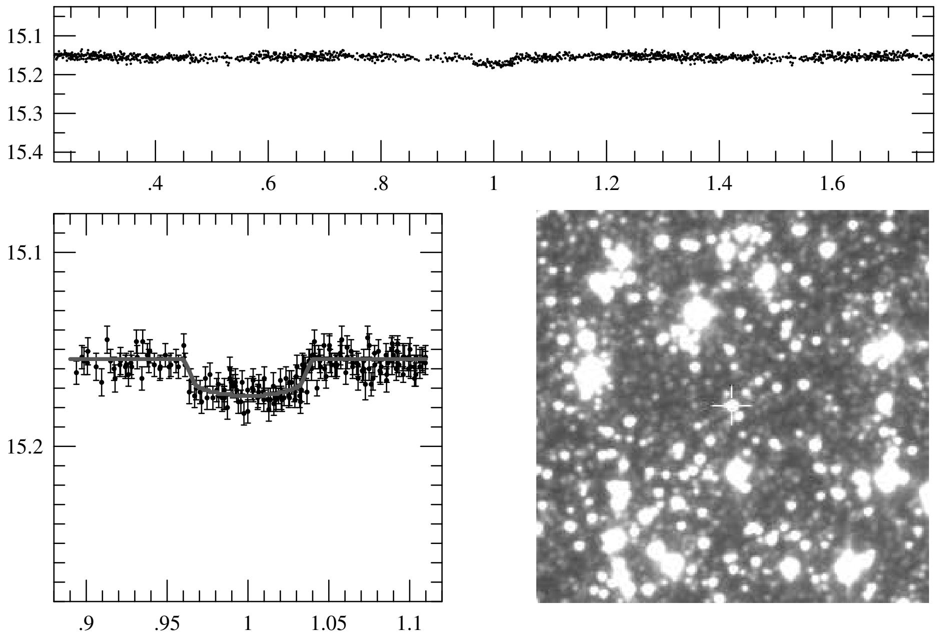
OGLE-TR-133 P=5.31075 (days)



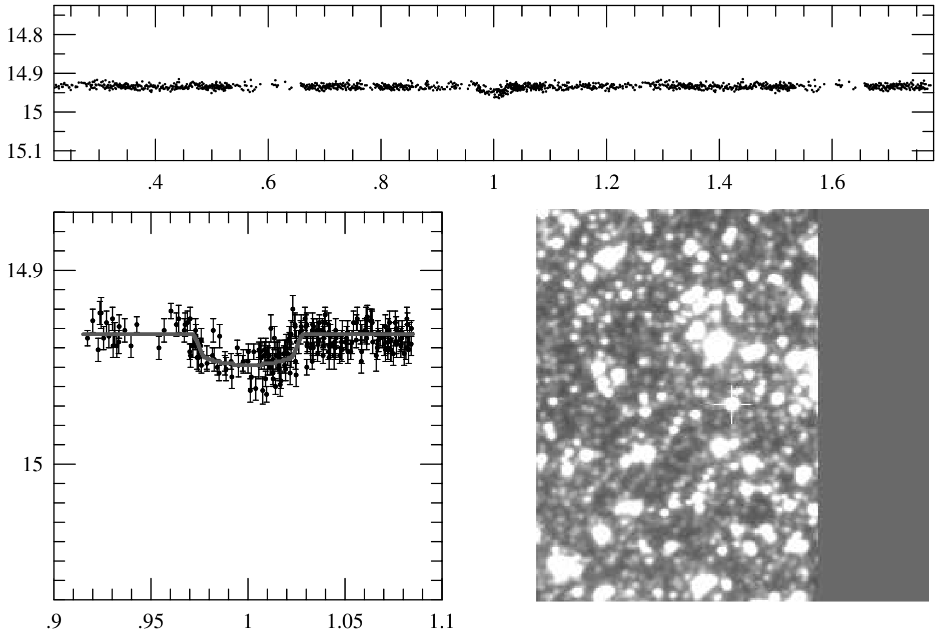
OGLE-TR-134 P=4.53720 (days)



OGLE-TR-135 P=2.57330 (days)



OGLE-TR-136 P=3.11580 (days)



OGLE-TR-137 P=2.53782 (days)