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Candidate extrasolar planet transits discovered in the Microlensing Observations in Astrophysics-I Galactic bulge data

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ABSTRACT

We present the results of a search for candidate planetary transits using the Microlensing Observations in Astrophysics-I (MOA-I) microlensing survey data in the Galactic bulge. To achieve sufficient photometric precision, the analysis was confined to a selected subset of stars on selected images. Periodicities of light curves were found with a Box fitting Least Squares (BLS) procedure. This yielded 12 candidates. The derived radii of the candidates ranged from 1.7 to 3.2 R_{J}, consistent with interpretations in terms of blended binaries, late M dwarfs or strongly irradiated giant planets. Follow-up spectroscopic observations would be required to identify actual planets amongst the candidates by radial velocity variations. The results confirm that microlensing surveys provide an effective means for finding candidate planetary transits. It is anticipated that the recently commissioned MOA-II telescope will provide further candidates in the future.

Key words: planets and satellites: formation – planets and satellites: general – binaries: eclipsing – planetary systems – stars: variables: other.

1 INTRODUCTION

The study of extrasolar planets is presently one of the more interesting fields in astronomy. The search for Earth-like planets is of course an exciting goal. At present, gravitational microlensing provides the only opportunity for detecting such planets (Bennett & Rhie 1996; Tyltler 1996; Abe et al. 2004) around solar-like stars with ground-based observations. Discoveries by the radial velocity technique of giant planets with orbits completely unlike those of Jupiter and Saturn are also exciting. Following the first such discovery in 1995 (Mayor & Queloz 1995), more than 130 giant planets were discovered. Many of these have high orbital eccentricities, and many others have small orbital radii of approximately 0.04 au. The latter group, the so-called 'hot Jupiters', are likely to have formed in outer orbits and subsequently migrated inwards (Lin, Bodenheimer & Richardson 1996; Trilling et al. 1999; Masset & Papaloizou 2003). The absence of such planets in the Solar system raises the question of whether or not it is special (Beer et al. 2004).

Besides the radial velocity and gravitational microlensing techniques, extrasolar planets may also be found and studied by the transit method. After several early pioneering works (Guinan et al. 1997; Deeg et al. 1998; Doyle et al. 2000), this method was first successfully applied to HD 209458b (Charbonneau et al. 2000; Henry et al. 2000; Mazeh et al. 2000), a planet orbiting a nearby star that was discovered by the radial velocity technique. An advantage of the transit technique is that it is readily applicable to planets orbiting both nearby and distant stars. The Optical Gravitational Lensing Experiment (OGLE) collaboration was the first to apply it to distant stars. Amongst a large sample of stars in the directions of the Galactic bulge and disc, which they monitored photometrically, they reported 137 planetary transit candidates (Udalski et al. 2002a,b,c), of which five were subsequently confirmed as being caused by planets (Konacki et al. 2003a,b; Bouchy et al. 2004; Konacki et al. 2004,

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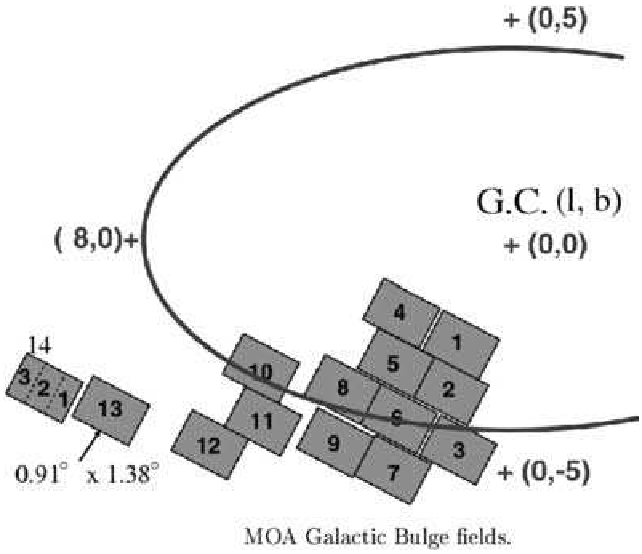

Figure 1. Schematic of the Microlensing Observations in Astrophysics-I bulge fields in the Galactic bulge used for the present work. The semicircle represents very roughly the shape of the Galactic bulge. The grey rectangles show the fields used in the present analysis.

2005; Pont et al. 2004). Very recently, a planet around a bright star, TrES-1, was discovered by the transit method (Alonso et al. 2004).

The transit detections have revealed evidence for a new class of planets. These are giant planets with very small orbital radii of approximately 0.025 au, so-called 'very hot Jupiters'. The transit observations have also enabled spectroscopic observations to be made of planetary atmospheres during transits. Vidal-Madjar et al. (2003) observed escaping hydrogen atoms from the planet HD209458b, a hot Jupiter. These planets are strongly irradiated by their parent stars, and may be evaporating. The combination of transit and radial velocity measurements for a system enables a more complete picture of the planet to be ascertained. The radial velocity data alone yield only the values of $M_{\mathrm{p}} \sin i$ and the orbital parameters semi-major axis and eccentricity (i being the inclination of the orbital plane as seen from the Earth). For a transit to occur at all, i must be very close to 90°, thus enabling a direct determination of M_{p} from the velocity data. The photometric depth of the transit light curve, combined with an estimate of the radius of the host star allows a determination of the planet's radius, and hence the combined data set enables the planet's average density to be determined.

The measured densities of hot Jupiters are puzzling. The radius of the planet HD209458b, for example, was found to be larger than that expected for a planet of its mass and age. The radius of a planet is expected to decrease with the age because of the gravitational contraction. Although it is possible that the larger value is caused by irradiation from the parent star, theoretical studies (Bodenheimer, Laughlin & Lin 2003; Chabrier et al. 2004) indicate this effect may be insufficient, at least for HD209458b. Other possibilities that have been raised include tidal heating by the central star (Bodenheimer et al. 2003) or undetected other companions (Chabrier et al. 2004).

It is apparent from the above that transit observations are useful for both finding and studying extrasolar planets. For the first task, photometric observations of a large number of stars are required. In this sense, the requirements are similar to those of the microlensing surveys in which millions of stars need to be monitored photometrically. The microlensing surveys may therefore be utilized to find candidate planetary transits. The OGLE microlensing collaboration, as referred to above, has already carried this out successfully. In this paper, we present additional candidate planetary transits that were discovered in the data base of the Microlensing Observations in Astrophysics (MOA) collaboration (Bond et al. 2001; Sumi et al. 2003).

2 OBSERVATIONS AND DATA REDUCTION

Observations for the MOA-I project have been carried out with a modified 61-cm Boller and Chivens Telescope at the Mt. John University Observatory in New Zealand. A computer-controlled drive system and wide-angle optics were installed on the telescope for the project. Most observations have been carried out with the MOA-cam2 camera. This has three 2048 × 4096 SITe CCD chips and provides a field of view (FOV) of 0.92 × 1.38 deg^2 (Yanagisawa et al. 2000). Two wide-band filters (R_{MOA} and B_{MOA}) are available. Most observations in the Galactic bulge have been carried out with the R_{MOA} filter. Occasional use of the B_{MOA} filter provides colour information. A standard exposure time of 3 min has been employed in the bulge. 14 bulge fields of total area 17.6 deg^2 are scanned cyclically a few times per clear night. Fig. 1 shows these fields. Occasionally, continuous observations are made of a single field to obtain continuous light curves of selected microlensing events, for example, those of very high magnification. The present

Table 1. Observational details for the planetary transit candidates. I and $V - I$ are I magnitude and observed difference between V and I magnitudes, respectively. ΔI, P and T_0 are the central transit depth in I magnitude, the period, and the time of transit, respectively, obtained by BLS fitting.

Name	Right ascension (RA)	Declination (Dec.)	I (mag)	$V - I$	ΔI	P (d)	T_0 (JD)
MOA-TR-1	$18^{\mathrm{h}}01^{\mathrm{m}}21^{\mathrm{s}}.78$	$-29^\circ46'39''.40$	14.04	1.03	0.046	2.25175	245 1646.0009
MOA-TR-2	$17^{\mathrm{h}}57^{\mathrm{m}}06^{\mathrm{s}}.00$	$-27^\circ59'36''.95$	14.37	1.63	0.047	1.79067	245 1645.3225
MOA-TR-3	$17^{\mathrm{h}}56^{\mathrm{m}}56^{\mathrm{s}}.09$	$-27^\circ45'54''.94$	14.33	1.28	0.043	3.44709	245 1644.5489
MOA-TR-4	$18^{\mathrm{h}}01^{\mathrm{m}}19^{\mathrm{s}}.36$	$-27^\circ41'46''.40$	14.96	1.34	0.047	2.42660	245 1645.1942
MOA-TR-5	$18^{\mathrm{h}}04^{\mathrm{m}}34^{\mathrm{s}}.20$	$-28^\circ51'27''.04$	14.39	0.97	0.034	1.27550	245 1647.0369
MOA-TR-6	$18^{\mathrm{h}}05^{\mathrm{m}}03^{\mathrm{s}}.60$	$-28^\circ52'57''.38$	15.34	1.27	0.034	1.99900	245 1647.3251
MOA-TR-7	$18^{\mathrm{h}}11^{\mathrm{m}}02^{\mathrm{s}}.37$	$-29^\circ21'50''.89$	15.23	1.02	0.054	3.04785	245 1647.8605
MOA-TR-8	$18^{\mathrm{h}}06^{\mathrm{m}}02^{\mathrm{s}}.26$	$-26^\circ55'34''.83$	14.57	1.28	0.037	1.62641	245 1647.0831
MOA-TR-9	$18^{\mathrm{h}}10^{\mathrm{m}}25^{\mathrm{s}}.77$	$-27^\circ49'07''.38$	14.53	1.32	0.073	1.69996	245 1645.9303
MOA-TR-10	$18^{\mathrm{h}}08^{\mathrm{m}}30^{\mathrm{s}}.45$	$-25^\circ59'52''.97$	15.18	1.37	0.054	1.18448	245 1646.3088
MOA-TR-11	$18^{\mathrm{h}}07^{\mathrm{m}}18^{\mathrm{s}}.13$	$-25^\circ21'48''.85$	13.19	1.31	0.063	2.54938	245 1646.9660
MOA-TR-12	$18^{\mathrm{h}}13^{\mathrm{m}}23^{\mathrm{s}}.47$	$-25^\circ49'47''.11$	13.96	1.29	0.049	1.97161	245 1647.1454

Table 2. Parameters of the stars and the companions. $V-I$ (corrected) is the extinction-corrected $V-I$. R_S is the radius of the central star. 'Estimated' column denotes the value estimated from the colour. 'Fitted' column denotes the value obtained from the fitting of the light curve. R_C/R_S is the ratio of the radii between the companion and the central star. R_C is the radius of the companion. These quantities may have uncertainties because of the assumptions we introduced (see text).

Name	$V-I$ (Corrected)	R_S ($R_\odot$) (Estimated)	(Fitted)	R_C/R_S	R_C (R_J)
MOA-TR-1	0.31	1.54	1.40	0.193	2.6
MOA-TR-2	0.27	1.63	1.60	0.188	2.9
MOA-TR-3	0.03	2.41	1.40	0.179	2.4
MOA-TR-4	0.35	1.47	1.27	0.205	2.5
MOA-TR-5	0.49	1.29	1.50	0.160	2.3
MOA-TR-6	0.73	1.09	1.40	0.164	2.2
MOA-TR-7	0.51	1.26	1.34	0.201	2.6
MOA-TR-8	0.45	1.33	0.90	0.189	1.7
MOA-TR-9	0.82	1.05	1.01	0.257	2.5
MOA-TR-10	0.53	1.24	1.20	0.217	2.5
MOA-TR-11	0.11	2.07	1.35	0.215	2.8
MOA-TR-12	0.46	1.31	1.94	0.170	3.2

analysis is based on data obtained by MOA-I during 2000, 2001 and 2002.

All frames were flat fielded and dark-frame subtracted following normal procedures. Photometry was then carried out on all frames using both DIA (Difference Image Analysis, Bond et al. 2001) and DOPHOT (Schechter, Mateo & Saha 1993). The DIA analysis yielded photometry of variable objects with a precision approaching the statistical limit (Alard & Lupton 1998), while DOPHOT was required to obtain calibrated magnitudes and colours. The DIA and DOPHOT data bases enabled a catalogue of calibrated light curves to be constructed. The $R_{\rm MOA}$ and $B_{\rm MOA}$ data were converted to standard I and V magnitudes through the empirical relations (Sumi et al. 2003):

$$I = R_{\rm MOA} + 26.2840 - 0.0969(B_{\rm MOA} - R_{\rm MOA}), \quad \text{(chip 1)} \quad (1)$$

$$I = R_{\rm MOA} + 26.3331 - 0.0969(B_{\rm MOA} - R_{\rm MOA}), \quad \text{(chip 2)} \quad (2)$$

$$I = R_{\rm MOA} + 26.5937 - 0.0969(B_{\rm MOA} - R_{\rm MOA}), \quad \text{(chip 3)} \quad (3)$$

$$V = B_{\rm MOA} + 26.3500 + 0.1600(B_{\rm MOA} - R_{\rm MOA}), \quad \text{(chip 1)} \quad (4)$$

$$V = B_{\rm MOA} + 26.8000 + 0.1600(B_{\rm MOA} - R_{\rm MOA}), \quad \text{(chip 2)} \quad (5)$$

and

$$V = B_{\rm MOA} + 27.1915 + 0.1600(B_{\rm MOA} - R_{\rm MOA}). \quad \text{(chip 3)} \quad (6)$$

The data base contains more than 5 000 000 stars. Cuts were made to exclude stars for which it was unlikely that planetary transits could be detected. Giants were removed first, as they are likely to be variable and too large for transit detection. They were removed using an extinction-corrected (Sumi et al. 2003) colour–magnitude diagram (CMD). Stars for which the average magnitude was uncertain by >0.014 were then excluded, to remove ordinary variable stars with large variabilities. The above procedure yielded a data base for further analysis of approximately 250 000 stars, still uncomfortably large. A re-analysis was therefore carried out.

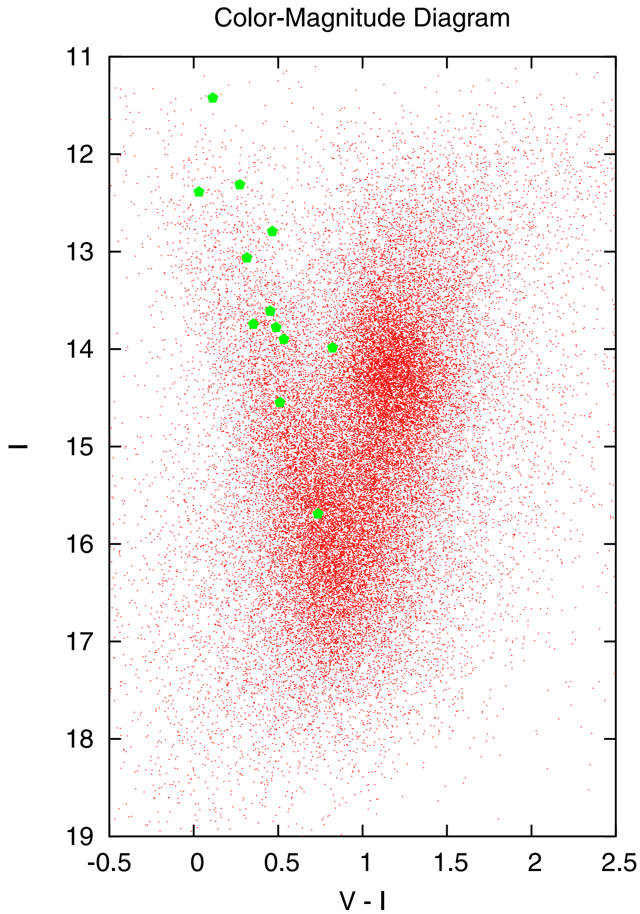

Figure 2. Extinction-corrected CMD. Green circles represent planetary transit candidates. Red dots represent sampled bulge stars.

Frames with bad seeing, bad weather or bad focus were removed to obtain better light curves. Also, frames taken in twilight or bright moonlight, and frames with satellite tracks, were removed. A total of about 16.2 per cent of all frames were excluded. Re-analysis of these frames by the above procedure still yielded a data base with too many variable stars. Stars with standard deviations of light flux greater than 2 per cent were therefore removed. This yielded 41 745 stars for further analysis.

We then searched for periodicities in the light curves of these stars that could be caused by planetary transits. In contrast to the periodic variations produced by variable stars and most eclipsing binaries, planetary transits have short durations and small flux changes. To detect such light curves efficiently, we applied a Box fitting Least Squares (BLS, Kovács, Zucker & Mazeh 2002) algorithm to a succession of light curves folded at a range of periods. This algorithm models the transits by simple rectangular wells and uses the χ^2 statistic to identify significant light curve deviations that match this model. We used periods for the folded light curves between 1.05 and 20 d. The lower limit was selected to avoid coincidence with the Earth's spin, while the upper limit was set to obtain sufficient data points in the folded light curves. This procedure, together with an eye-scan of the light curves, yielded 52 stars with possible planetary companions.

To obtain physical parameters, more detailed light curve analyses were necessary. The observed light curves were broadened and rounded compared to the BLS model because of the finite

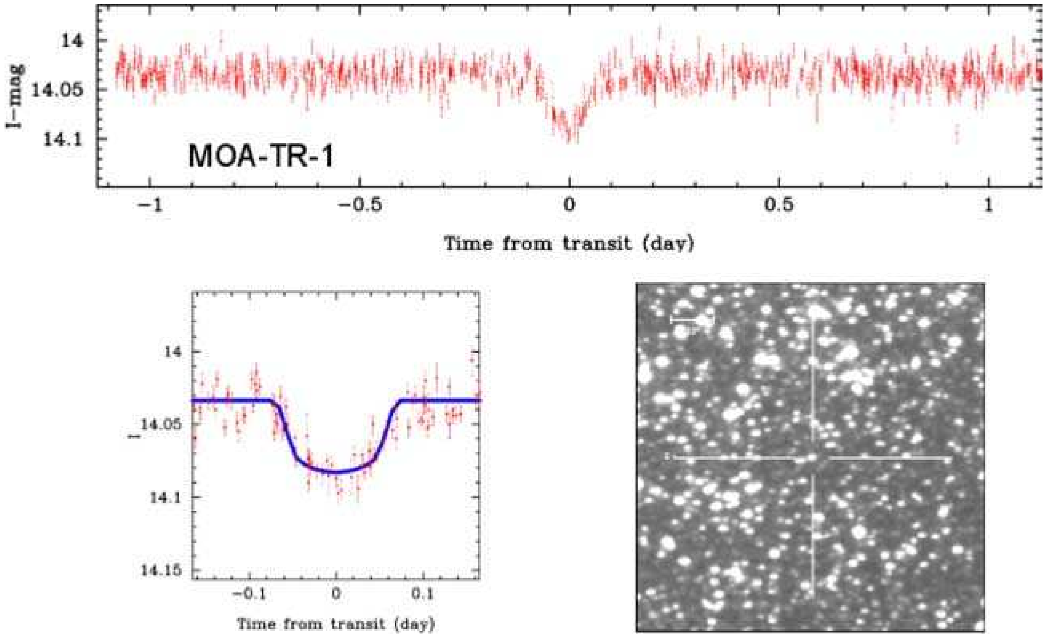

Figure 3. Light curve folded by periods (top), enlarged transit light curve (bottom left), and finding chart (bottom right) for MOA-TR-1. The scale bar in the finding chart represents 20 arcsec.

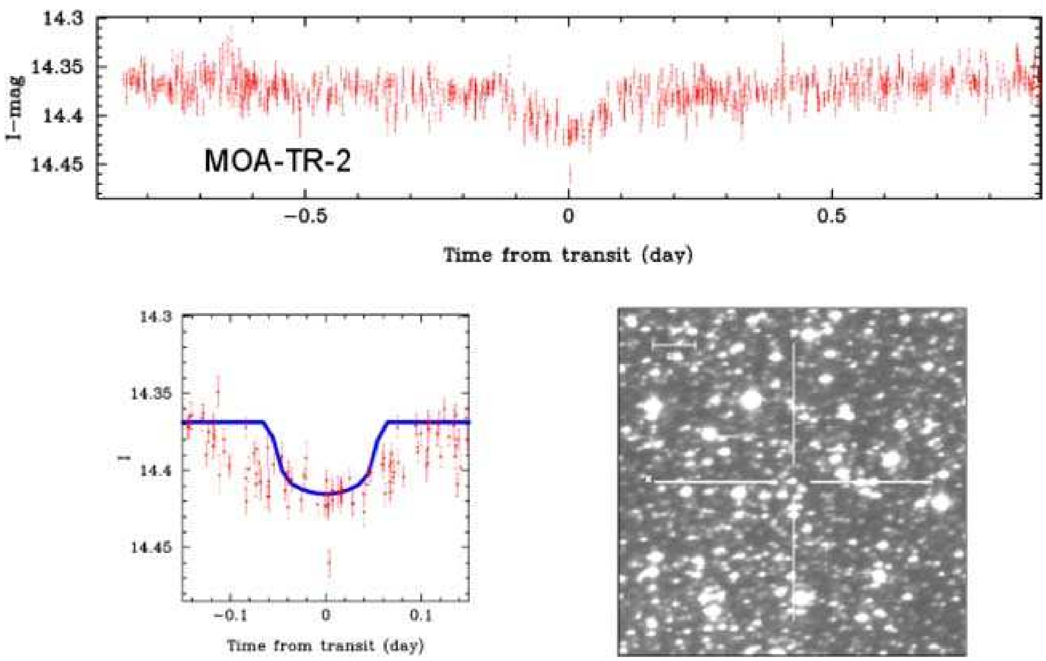

Figure 4. Light curve folded by periods (top), enlarged transit light curve (bottom left), and finding chart (bottom right) for MOA-TR-2. The scale bar in the finding chart represents 20 arcsec.

sizes of the companion and the limb darkenings on the central stars. We assumed symmetric linear limb darkening (Al-Naimiy 1978):

$$B(u) = B(0)\,(1 - c\,u), \tag{7}$$

where $B(u)$ is the surface brightness, $u = r/R_S$ is the normalized distance from the centre of the star in the plane perpendicular to the observer, and c is the limb darkening coefficient. In this analysis, we assumed $c = 0.5$. Assuming the inclination of the orbit is 90°, the maximum fractional drop of the flux in the transit, ΔF is expressed as

$$\Delta F = \frac{\int_0^{R_C/R_S} B(u)\,u\,\mathrm{d}u}{\int_0^1 B(u)\,u\,\mathrm{d}u}, \tag{8}$$

where R_C is the radius of the companion and R_S is the radius of the central star. The duration of the transit, t_T is written as

$$t_T = \frac{P}{\pi}\frac{R_S + R_C}{a}, \tag{9}$$

where P is the period, and a is the radius of the companion orbit. From Kepler's third law, P and a are related and are expressed in

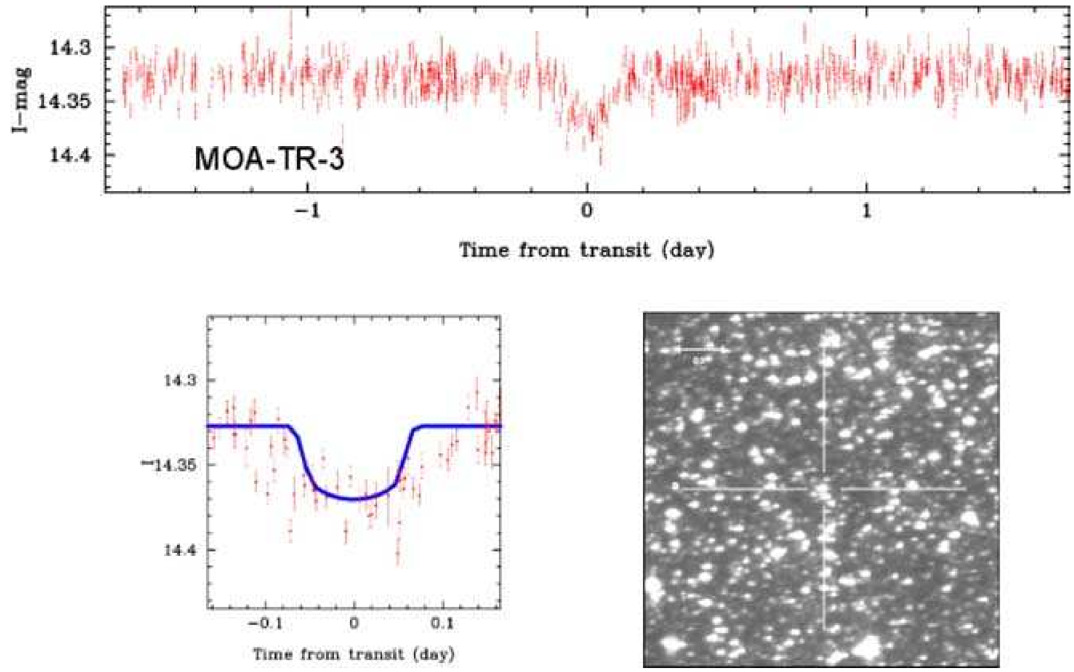

Figure 5. Light curve folded by periods (top), enlarged transit light curve (bottom left), and finding chart (bottom right) for MOA-TR-3. The scale bar in the finding chart represents 20 arcsec.

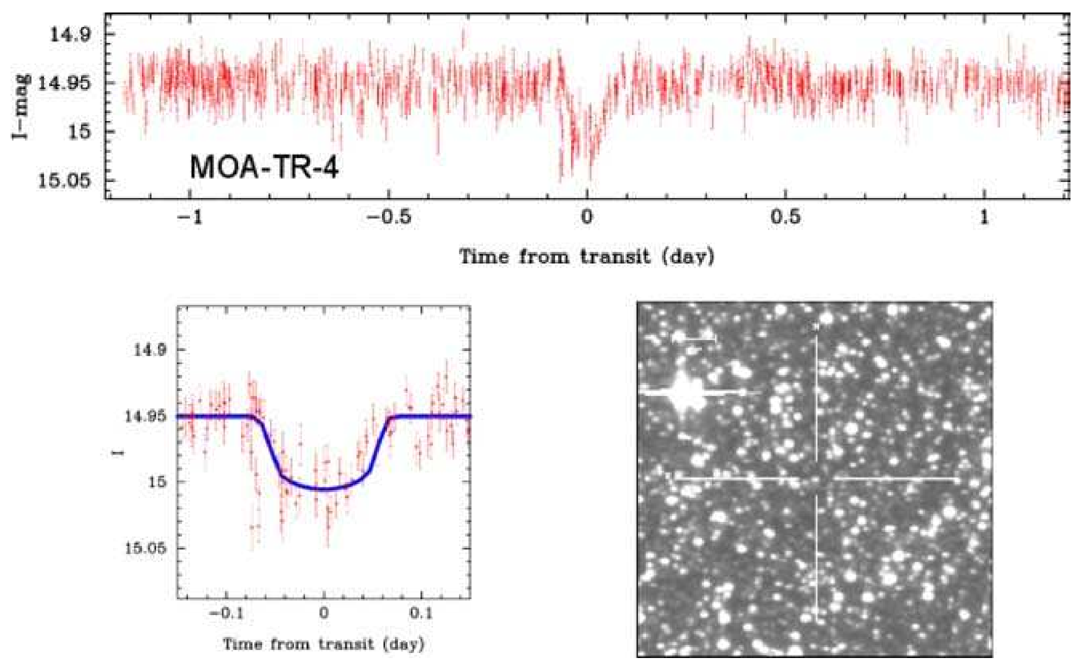

Figure 6. Light curve folded by periods (top), enlarged transit light curve (bottom left), and finding chart (bottom right) for MOA-TR-4. The scale bar in the finding chart represents 20 arcsec.

terms of the masses of the central star and the companion. As the mass of a planet is very small, we neglect its mass. Then we obtain

$$a = \left[G M_{\mathrm{S}} \left(\frac{P}{2\pi} \right)^2 \right]^{1/3}. \tag{10}$$

P was obtained by BLS fitting. Thus, we can calculate a from P and M_{S}. For main-sequence stars, it is known that there is empirical relation between the radius and the mass. We assumed (Allen 1973)

$$M_{\mathrm{S}}/\mathrm{M}_{\odot} = 2.196 R_{\mathrm{S}}/\mathrm{R}_{\odot} - 2.613, \; (R_{\mathrm{S}} \geqslant 2.5\,\mathrm{R}_{\odot}) \tag{11}$$

and

$$M_{\mathrm{S}}/\mathrm{M}_{\odot} = 1.326 R_{\mathrm{S}}/\mathrm{R}_{\odot} - 0.2764, \; (R_{\mathrm{S}} \leqslant 2.5\mathrm{R}_{\odot}), \tag{12}$$

where M_{S} is the mass of the central star. An initial value of R_{S} is estimated from the colour. We assumed (Allen 1973)

$$R_{\mathrm{S}}/\mathrm{R}_{\odot} = 10^{-1.332(V-I)+0.2107} + 0.929, \tag{13}$$

where $V - I$ is the extinction-corrected value. Then the fittings were performed with equations (8) and (9), together with equations (10)–(12) to obtain R_{S} and R_{C}.

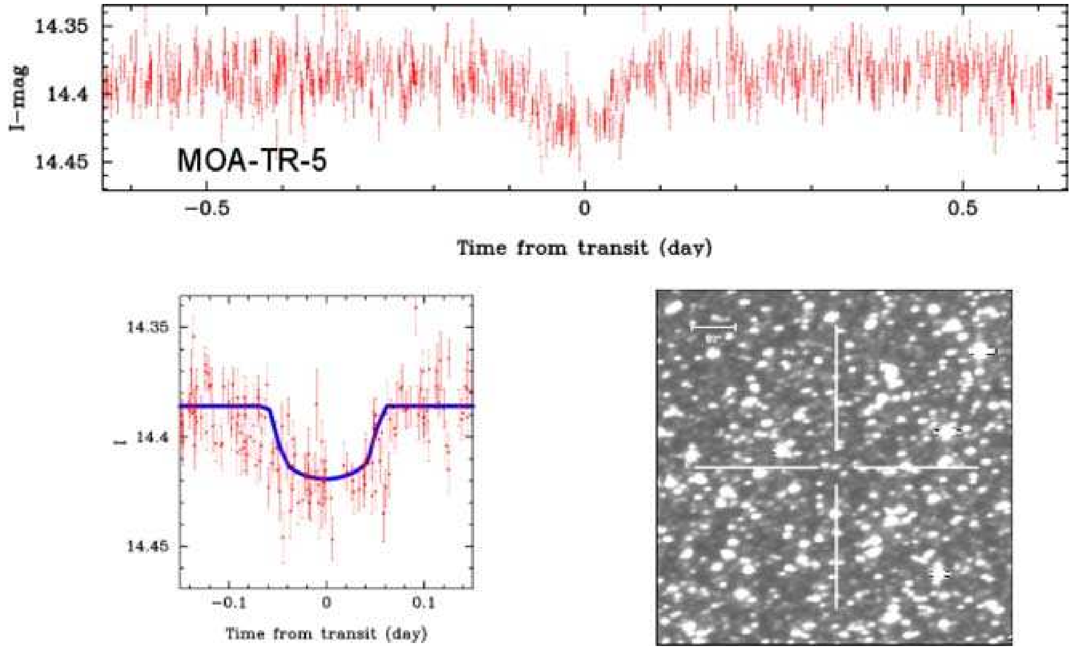

Figure 7. Light curve folded by periods (top), enlarged transit light curve (bottom left), and finding chart (bottom right) for MOA-TR-5. The scale bar in the finding chart represents 20 arcsec.

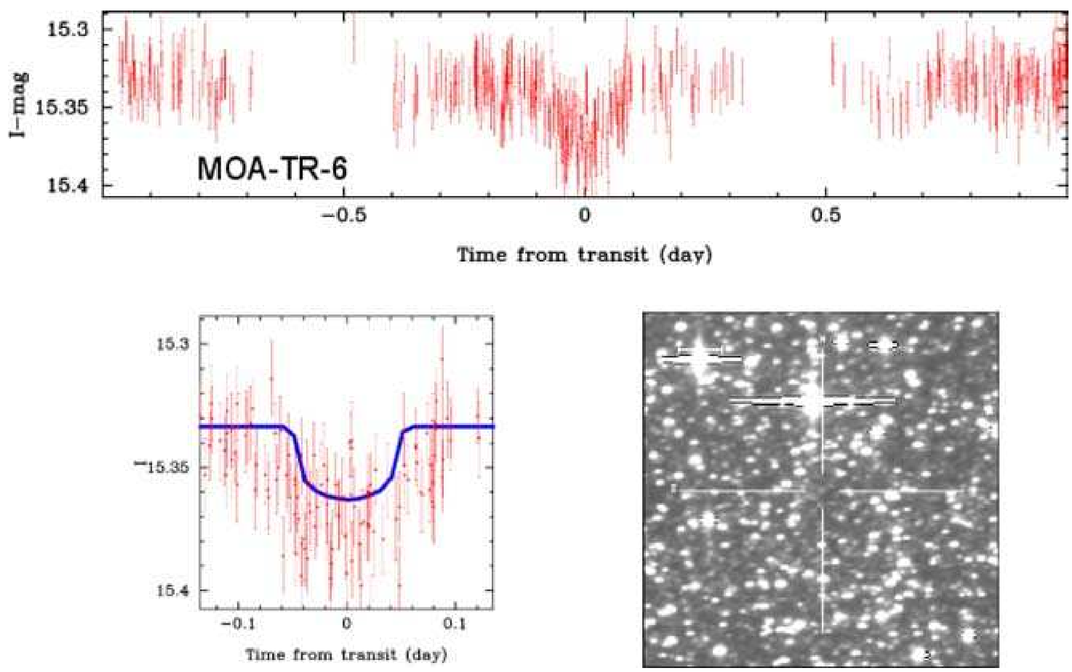

Figure 8. Light curve folded by periods (top), enlarged transit light curve (bottom left), and finding chart (bottom right) for MOA-TR-6. The scale bar in the finding chart represents 20 arcsec.

Some of the companion radii were very large. Companions with estimated radii $R_C > 0.34\,R_\odot$ were identified as stellar companions and rejected. Examination of the light curves of several of the candidate stars showed that they had sharp V-shaped light curves. These were identified as grazing eclipses (Drake & Cook 2004). Removing these, 12 stars remained as final candidates with possible planetary transits. Observed and derived parameters of the 12 candidates are given in Tables 1 and 2, respectively. We introduced several assumptions to derive parameters. Thus, the values in Table 2 may have uncertainties. The assumption of the 90° inclination is expected to cause underestimations of R_S and R_C values, whereas the ratio R_C/R_S is still reliable. The R_S values estimated from the colours have another kind of uncertainty. The present data were taken along the Galactic bulge where large extinctions by

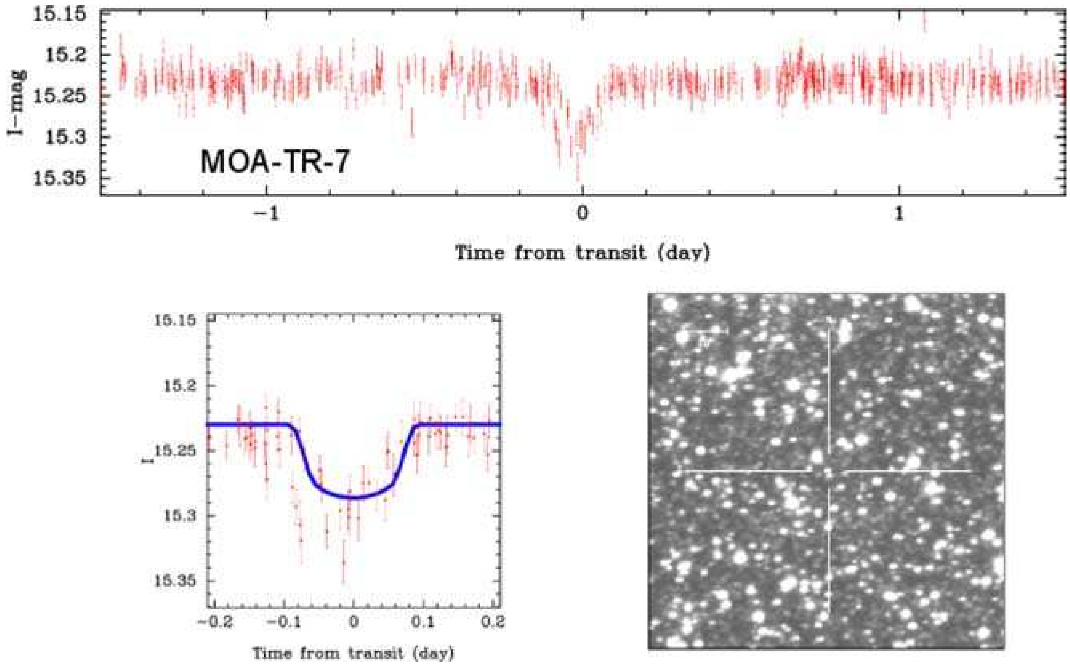

Figure 9. Light curve folded by periods (top), enlarged transit light curve (bottom left), and finding chart (bottom right) for MOA-TR-7. The scale bar in the finding chart represents 20 arcsec.

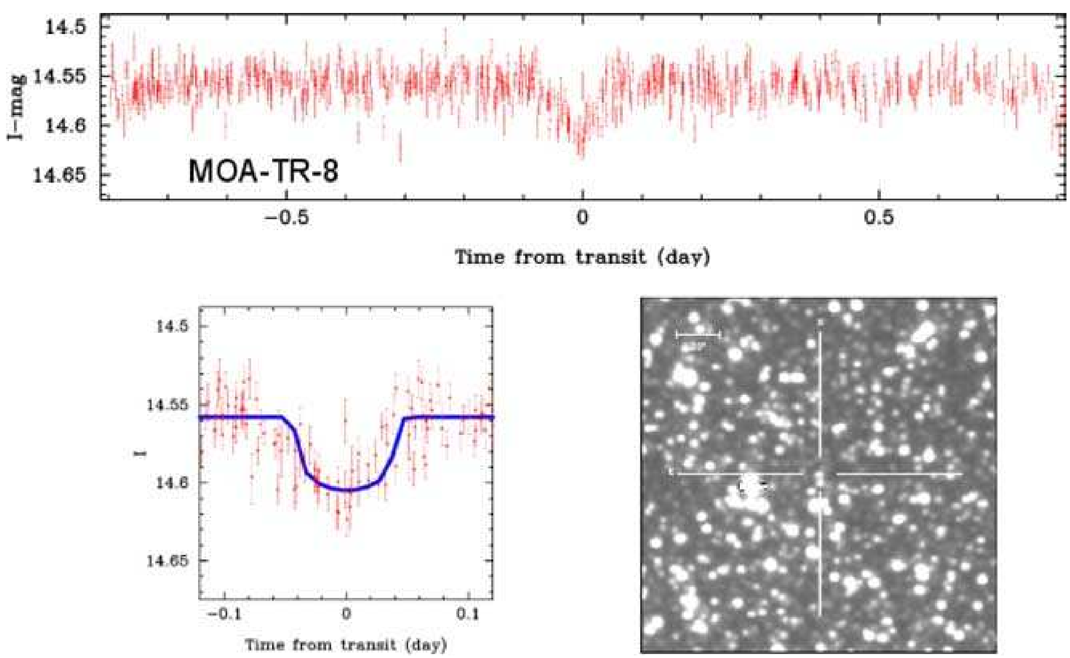

Figure 10. Light curve folded by periods (top), enlarged transit light curve (bottom left), and finding chart (bottom right) for MOA-TR-8. The scale bar in the finding chart represents 20 arcsec.

interstellar gases are expected. We corrected (Sumi et al. 2003) this effect using the extinction map on the celestial plane. But such correction may be imprecise because of the limited knowledge of the interstellar gas and the distance to the star. To obtain better estimates to those parameters, precise determinations of the spectral types by follow-up observations would be effective. On the other hand, the values in Table 1 are expected to be precise because they are determined directly from the data. The number of observations used to obtain these values is between 400 and 900 for each star. However, only the observations during transits (37 to 169 for each star) contribute to the determination of P and T_0, and observations at the edges of the transits are particularly important. The number of such observation in our present data obviously limits the precision of our derived P and T_0 values. However, we have briefly inspected

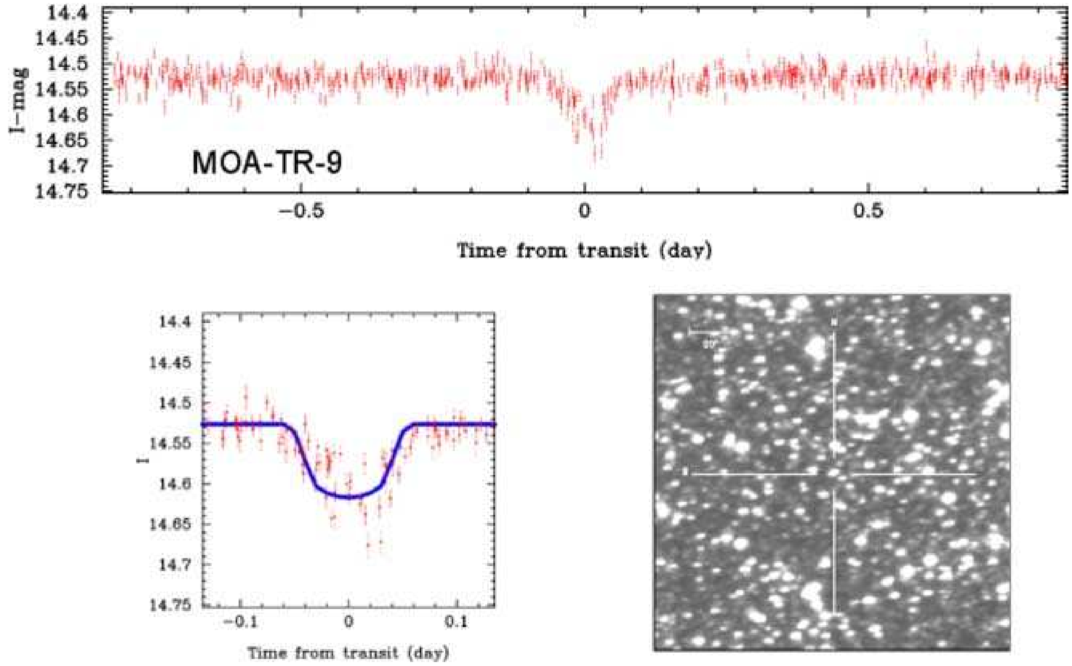

Figure 11. Light curve folded by periods (top), enlarged transit light curve (bottom left), and finding chart (bottom right) for MOA-TR-9. The scale bar in the finding chart represents 20 arcsec.

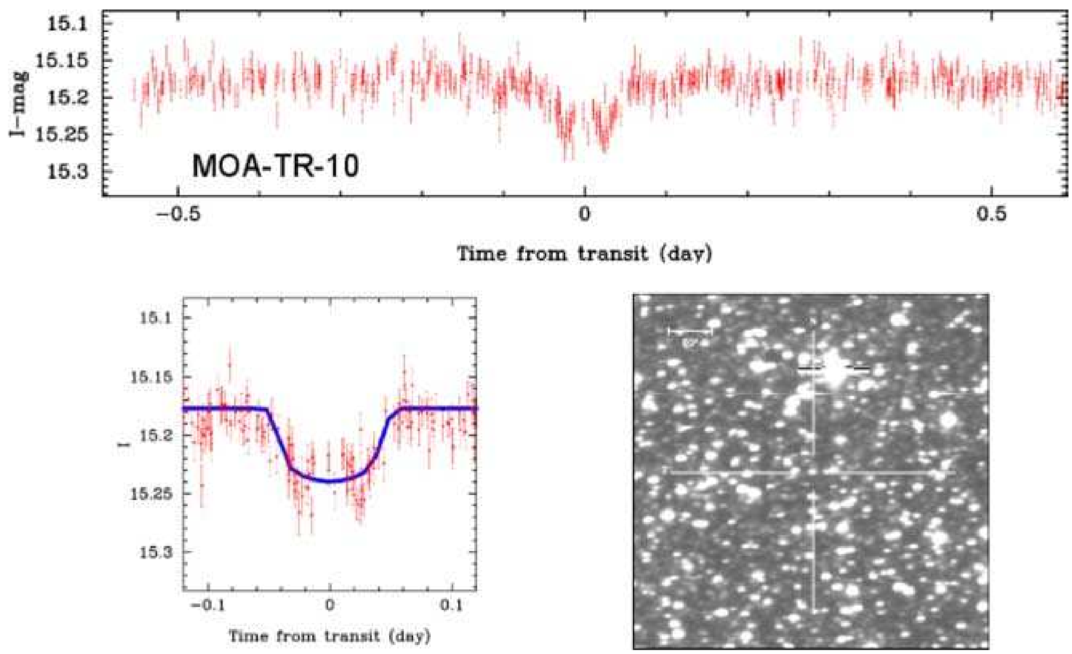

Figure 12. Light curve folded by periods (top), enlarged transit light curve (bottom left), and finding chart (bottom right) for MOA-TR-10. The scale bar in the finding chart represents 20 arcsec.

more recent data obtained during the 2003 and 2004 observing seasons and confirmed that the transits are repeating with the derived periods.

3 CANDIDATE PLANETARY TRANSITS

Fig. 2 shows the extinction-corrected CMD for the planetary transit candidates and sampled bulge stars. Most of the candidates lie on or near the main sequence, as expected. The light curves folded by periods, enlarged transit light curves, and finding charts are shown in Figs 3–14. The light curves exhibit the expected characteristics of transits by small companions. However, they may also be interpreted in terms of blended binaries. Further information, either spectroscopic or multicolour photometric, could identify the blended binaries. The remainder should consist of stars being transited by small objects, either planets or brown or M dwarfs. Radial

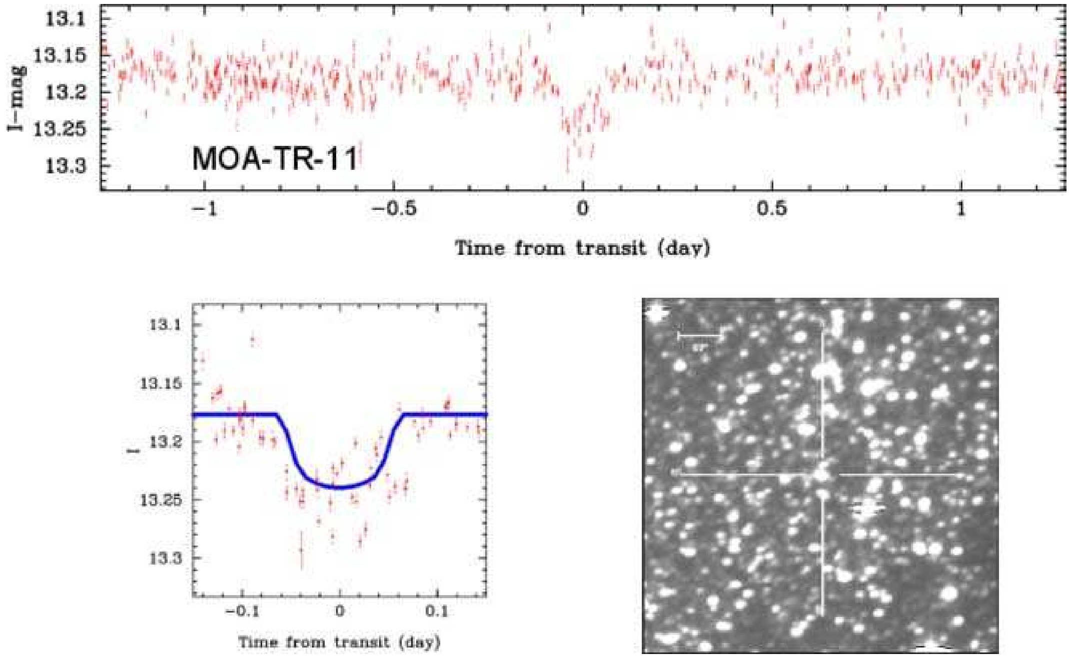

Figure 13. Light curve folded by periods (top), enlarged transit light curve (bottom left), and finding chart (bottom right) for MOA-TR-11. The scale bar in the finding chart represents 20 arcsec.

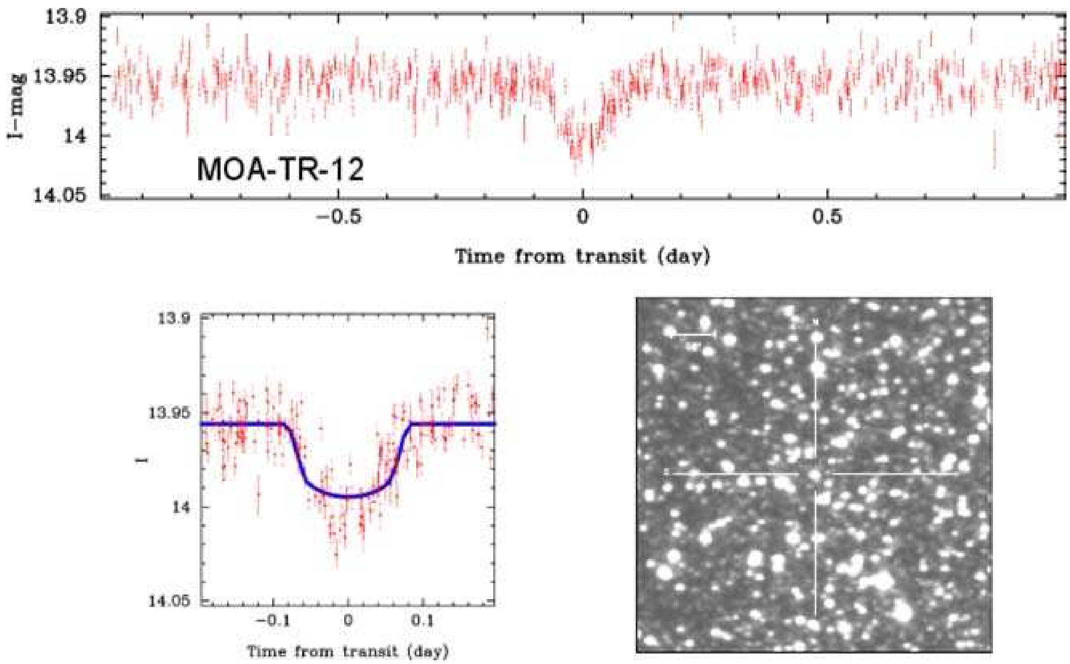

Figure 14. Light curve folded by periods (top), enlarged transit light curve (bottom left), and finding chart (bottom right) for MOA-TR-12. The scale bar in the finding chart represents 20 arcsec.

velocity measurements could identify the planets amongst this sample. As the candidate stars are faint ($13.19 \geqslant I \geqslant 15.34$), a large telescope ($\geqslant$10 m) would be required to achieve the required velocity discrimination.

The periods of the candidates range from 1.18 to 3.45 d. These are consistent with identifications as either hot Jupiters or very hot Jupiters. However, the estimated radii of the companions range from 1.7 to $3.2R_{\mathrm{J}}$, and these appear unexpectedly large for most planets, although not outside the range for some predictions. Theoretical studies of the evolution of a planet that is strongly irradiated by its host star indicate that its radius decreases with age (Bodenheimer et al. 2003; Chabrier et al. 2004; Gu et al. 2004). Young planets may have large radii, $> 2R_{\mathrm{J}}$. Also, relatively low-mass, hot planets with $<0.11M_{\mathrm{J}}$ and temperature $>$2000 K can have large radii, $>1.75R_{\mathrm{J}}$, if they do not possess a solid-state core (Bodenheimer et al. 2003). Other possibilities for expanded planets are those that have been tidally heated, either by their host star or a companion star (Chabrier et al. 2004; Gu et al. 2004). It is therefore possible that our candidates include some real planets.

As mentioned above, the present sample of planetary transit candidates was found amongst the normal survey data of the MOA-I microlensing project. A more efficient procedure for finding planetary transits amongst such surveys is to employ a higher-than-normal repetition rate. This was the procedure that was successfully introduced by the OGLE group (Udalski et al. 2002a). Our observations have shown that planetary candidates may, however, be found as a by-product of normal survey operations.

The present observations were made with the MOA-I telescope at the Mt. John University Observatory. This has an aperture 61 cm and an FOV of about 1.3 deg^2. Observations will shortly commence with the MOA-II telescope at the same site. This will have an aperture of 1.8 m and an FOV of about 2.2 deg^2. We expect that additional candidate planetary transits with smaller amplitudes will be found with this telescope.

4 CONCLUSIONS

We have reanalysed the MOA-I Galactic bulge microlensing search data to find planetary transits. 12 stars are selected as candidates of possible planetary transits. The radii obtained from transit fittings are 1.7–3.2R_J. The most probable explanation is that they are blended binaries or late M dwarfs. However, evolution models of strongly irradiated planets indicate that planets may have such large radii in some conditions. Thus, the present candidates may include planets. Radial velocity measurements are necessary to confirm their identities. Although our observations were not optimized to a transit search, we found 12 candidates from our microlensing search data. This shows ordinary microlensing surveys are effective also as transit surveys. The MOA group is constructing a new 1.8-m telescope and will start MOA-II observations in 2005. Finding more candidates with the new telescope is expected.

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