Behind the Scenes of the Discovery of Two Extrasolar Planets: ESO Large Programme 666

Dante Minniti[1,2]
Claudio Melo[3]
Dominique Naef[3]
Andrzej Udalski[4,5]
Frédéric Pont[6]
Claire Moutou[7]
Nuno Santos[8]
Didier Queloz[6]
Tsevi Mazeh[9]
Michel Gillon[6]
Michel Mayor[6]
Stephane Udry[6]
Rodrigo Diaz[10]
Sergio Hoyer[11]
Sebastian Ramirez[1]
Grzegorz Pietrzynski[4,12]
Wolfgang Gieren[12]
Maria Teresa Ruiz[11]
Manuela Zoccali[1]
Omer Tamuz[9]
Abi Shporer[9]
Marcin Kubiak[4,5]
Igor Soszynski[4,5]
Olaf Szewczyk[4,5]
Michal Szymanski[4,5]
Krzysztof Ulaczyk[4,5]
Lukasz Wyrzykowski[5,13]

1 Departamento de Astronomía y Astrofísica, Pontificia Universidad Católica de Chile, Santiago, Chile
2 Specola Vaticana, Città del Vaticano, Italy
3 ESO
4 Warsaw University Observatory, Poland
5 The OGLE Team
6 Observatoire de Genève, Sauverny, Switzerland
7 Laboratoire d'Astrophysique de Marseille, France
8 Centro de Astrofísica, Universidade do Porto, Portugal
9 School of Physics and Astronomy, R. and B. Sackler Faculty of Exact Sciences, Tel Aviv University, Israel
10 Instituto de Astronomía y Física del Espacio, Buenos Aires, Argentina
11 Departmento de Astronomía, Universidad de Chile, Santiago, Chile
12 Departamento de Astronomía, Universidad de Concepción, Chile
13 Institute of Astronomy, University of Cambridge, United Kingdom

This is the story of the Large Programme 666, dedicated to discover sub-stellar objects (extrasolar planets and brown dwarfs), and to measure their masses, radii, and mean densities. We hunt selected OGLE transit candidates using spectroscopy and photometry in the 'twilight zone', stretching the limits of what is nowadays possible with the VLT.

The programme

Transiting extrasolar planets are essential to our understanding of planetary structure, formation and evolution outside the Solar System. The observation of transits and secondary eclipses gives access to such quantities as a planet's true mass, radius, density, surface temperature and atmospheric spectrum.

The OGLE search for transiting planets and low-mass stellar companions has been the first photometric transit survey to yield results. Follow-up of existing OGLE low-amplitude transit candidates prior to our Large Programme has uncovered five extrasolar planets and has yielded the measurement of their radii and therefore their densities. Despite these successes, many important points remain to be understood: how hot Jupiters form, how they evolve, what is the frequency of hot Jupiters, why the density range of hot Jupiters is so large, etc. The main difficulty in answering these questions is the limited number of transiting planets detected so far.

Our Large Programme 177.C-0666 (LP666 for short) proposed to enlarge this sample of confirmed OGLE extrasolar planets, and also to populate the mass-radius diagram for low-mass objects, including planets, brown dwarfs and late M-type stars. 177 transiting candidates from the OGLE survey had been published when we started this LP666, and as part of this programme three new OGLE seasons produced 62 new candidates.

We used VLT+FLAMES to obtain radial velocity orbits in order to measure the mass of all interesting OGLE transiting candidates, and also VLT+UVES and VLT+FORS to measure their precise radius from high-resolution spectroscopy of the primary and high-definition transit light curves.

The telescopes and instruments

We use the Very Large Telescope UT2 in order to measure radial velocities, and UT1 and 2 for photometry in order to measure the transits. Most of the spectroscopic observations required real-time decisions to be taken and therefore were made in visitor mode, whereas photometry collected at precise transit times was carried out in service mode by expert mountain personnel.

The spectroscopic runs were done with FLAMES in GIRAFFE mode which allows simultaneously more than 100 stars to be observed at resolutions ranging from about 5000 to 20000. At the same time, the other seven to eight fibres feed UVES at the other Nasmyth focus of the telescope, collecting spectra with a resolution of 50000. Both GIRAFFE and UVES allow us to acquire spectra of a comparison lamp simultaneously with the target observations. The lamp spectrum is used afterwards to correct spectrograph shifts. This is essential in order to be able to measure radial velocity with a precision of a few m/s. Accurate radial velocity measurements require high-resolution spectra, for this reason we placed the best candidates in the UVES fibres in order to measure more accurate velocities. The photometric runs were acquired with FORS1 or FORS2, yielding milli-magnitude photometry and a high-quality light curve, essential to derive accurate physical parameters for the transiting planets.

The team preparations

Three teams were competing for the same resources: the OGLE team, the Geneva team, and the Chilean team. The idea arose of working together and the final details were discussed at the workshop in Haute-Provence "10 years of 51 Peg". In preparation for this Large Programme, we had to re-examine the OGLE database to check old candidates and improve the ephemeris, and to run the OGLE pipelines to select new candidates. Our teams have put together their respective spectroscopic and photometric databases in order to select the most promising candidates, but it was not easy to decide which were these best candidates, and this was extensively discussed by many team members. The spectroscopic run of February 2006 by the Swiss team was used to cull some candidates. The photometric run of the last period of March 2006 of the Chilean team was used to observe some of these most promising candidates. We finally started the planet hunting for this Large Programme in April 2006 with many promising candidates.

The first step is to acquire radial-velocity information for the most promising OGLE planetary transit candidates, and to identify real transiting planets among them. This requires five to eight radial velocity points with UVES in good observing conditions. As the OGLE candidates are disposed in a few square degrees of the sky, a few of them (typically two to five targets) can be observed simultaneously using the FLAMES configuration. The weather conditions of this first run were rather poor, with five clouded nights and three clear nights. As our targets are faint and we need < 100 m/s radial velocity accuracy, the clouded nights were of very limited use, despite the occasional gaps in the clouds.

This Large Programme had another component, many hours of service observations on FORS to obtain high-accuracy measurements of the transits of the planets that we expected to discover. In fact, the results of these initial runs suggested three possible planets, but because of bad weather we could not reach solid conclusions on these objects. Due to the bad weather, it was more important at this initial stage to recover some of the spectroscopic time that was lost. We therefore requested to ESO to swap some of our photometric time for spectroscopic time in service mode, a request that was kindly (and quickly) approved.

The candidates

We measured and analysed the various candidates found during the OGLE season III, from OGLE-TR-138 to OGLE-TR-177. This was done using new data from the present LP666 in combination with data already in hand. A detailed publication for these candidates is in preparation. This paper would be a large effort, like the previous papers by Pont et al. (2005) for Carina, and Bouchy et al. (2005) for the Galactic Bulge. In addition, the flexibility of the OGLE telescope has allowed us to obtain the candidates needed, producing a new set of candidates for this LP666, which we have followed-up during periods P78–P82. These were selected carefully among periodic low-amplitude transits observed with the Warsaw telescope during the last seasons: season IV from candidates OGLE-TR-178 to TR-200; and season V from candidates OGLE-TR-201 to TR-219. These are listed in Table 1. New candidates from season VI (up to OGLE-TR-238) are still being analysed.

The spectroscopic runs had two goals: (1) to sort out the non-planetary candidates; and (2) to measure an orbital motion for the planetary candidates. The need to discard as quickly as possible the impostors required that data reduction and radial velocity measurement had to be done in real time. This was achieved by a combination of the FLAMES/UVES pipeline and our own code. The previous nights results were analysed by our team

Object	Period	*I*	Depth	Status
OGLE-TR-178	2.97115	16.56	0.016	faint target, not observed
OGLE-TR-179	12.67106	15.13	0.034	flat CCF
OGLE-TR-180	1.99601	16.74	0.012	faint target, not observed
OGLE-TR-181	2.3896	16.29	0.01	fast rotator (synch.?)
OGLE-TR-182	3.98105	15.86	0.01	transiting planet
OGLE-TR-183	4.78217	15.32	0.015	fast rotator (synch.?)
OGLE-TR-184	4.92005	15.57	0.015	fast rotator (synch.?)
OGLE-TR-185	2.78427	16.72	0.035	fast rotator (synch.?)
OGLE-TR-186	14.81481	16.54	0.054	faint target, not observed
OGLE-TR-187	3.45686	14.07	0.008	double-lined spectroscopic binary (SB2)
OGLE-TR-188	6.87663	16.38	0.031	blend of two line systems
OGLE-TR-189	1.73937	15.03	0.006	not observed
OGLE-TR-190	9.38262	16.06	0.043	not observed
OGLE-TR-191	2.51946	15.57	0.007	fast rotator (synch.?)
OGLE-TR-192	5.42388	14.41	0.008	flat CCF
OGLE-TR-193	2.95081	14.99	0.008	not observed
OGLE-TR-194	1.59492	14.69	0.006	flat CCF
OGLE-TR-195	3.62174	14.19	0.006	not obseved
OGLE-TR-196	2.1554	15.57	0.012	fast rotator (synch.?)
OGLE-TR-197	2.40587	14.59	0.019	flat CCF
OGLE-TR-198	13.63141	15.44	0.018	not observed
OGLE-TR-199	8.8347	14.88	0.017	single-lined spectroscopic binary (SB1)
OGLE-TR-200	6.48845	15.63	0.023	not observed
OGLE-TR-201	2.368	15.6	0.016	fast rotator
OGLE-TR-202	1.6545	13.6	0.017	not observed
OGLE-TR-203	3.3456	15.6	0.014	not observed
OGLE-TR-204	3.1097	14.8	0.026	SB2
OGLE-TR-205	1.7501	16	0.015	not observed
OGLE-TR-206	3.2658	13.8	0.006	no variation
OGLE-TR-207	4.817	14.3	0.021	SB2
OGLE-TR-208	4.5025	15.3	0.022	SB2
OGLE-TR-209	2.2056	15	0.022	no variation
OGLE-TR-210	2.2427	15.2	0.032	fast rotator
OGLE-TR-211	3.6772	14.3	0.008	planet
OGLE-TR-212	2.2234	16.3	0.016	blend?
OGLE-TR-213	6.5746	15.3	0.036	SB2
OGLE-TR-214	3.601	16.5	0.023	SB1
OGLE-TR-215	4.9237	14.8	0.016	no variation
OGLE-TR-216	1.9763	14.6	0.011	blend?
OGLE-TR-217	5.7208	16.1	0.037	no CCF
OGLE-TR-218	2.2488	14.5	0.02	fast rotator
OGLE-TR-219	9.7466	15.1	0.032	SB2

Table 1. List of targets selected for follow-up from OGLE seasons IV and V. The photometric period, *I*-band magnitude and transit depth are based on the OGLE data. The last column is our final assessment of the status of the OGLE transit candidates after the spectroscopic follow-up with FLAMES.

members in Europe. Based on their feedback, FLAMES configuration files were updated or simply discarded. We will here discuss the first two confirmed planets, but along this work we have analysed about 100 OGLE candidates (from OGLE-TR-138 to OGLE-TR-238), including several new ones that were selected for this programme from OGLE seasons IV, V and VI.

The non-planets

A vast number of candidates are produced by OGLE, which needed to be confirmed spectroscopically and photometrically. Therefore, a large part of the work we did was dedicated to eliminate non-planetary candidates from the OGLE selection.

The shape of the cross correlation function (CCF) can be efficiently used for bad candidate detection and rejection. Figure 1 represents the CCFs obtained for some new P78–P80 targets for which we were able to conclude, after a single FLAMES observation, that a follow-up was useless. All these data were obtained in the February 2007 run, when five new fields were started. Only one contained a good candidate out of 10 new objects; that is OGLE-TR-235, shown in Figure 2. From the photometric point of view, the light curve produced by OGLE was always compatible with a planet. That is one of the reasons why a follow-up is mandatory (the other important reason being the need to determine an accurate planetary mass, of course).

Following the procedure described in the papers, we have discarded several candidates. For example, we analysed 42 new OGLE candidates, finding two planets plus the following:
– obvious or suspected single- or double-lined spectroscopic binaries (blend, binary with high-mass companion): 11 candidates;
– broad CCF (synchronised, fast rotator): 9 candidates;
– no CCF dip detected, no radial velocity (false detections, faint candidates): 8 candidates;
– too faint candidates, outside the field (not observed): 11 candidates;
– others: 3 candidates.

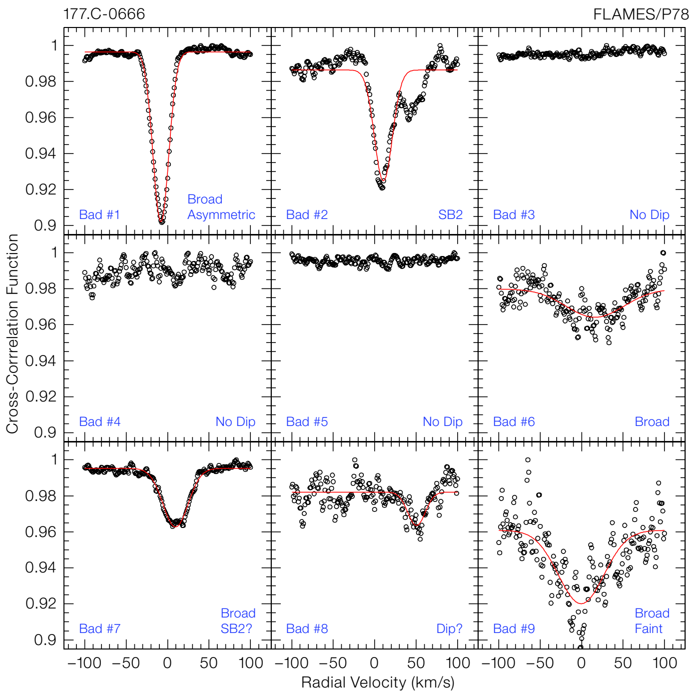

Figure 1. The cross-correlation functions (CCF) from the spectra of the different candidates shown as an example of all the typical bad CCF cases.

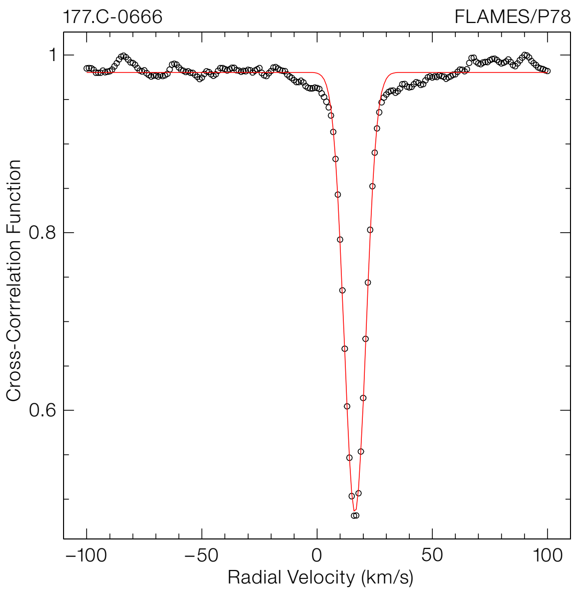

Figure 2. The CCF of a good candidate (OGLE-TR-235).

FLAMES has been very efficient in identifying bad candidates. It is not an exaggeration to say that FLAMES-UVES is in a league of its own for follow-up of faint transit candidates, such as the ones discovered by OGLE. We have observed the complete sample of all accessible new OGLE candidates. We note that all the data acquired with FLAMES-UVES are fully reduced already. We have so far concentrated on looking for the best planetary candidates and measuring their parameters. In the near future we would go back and sift through the whole dataset, looking for low-mass companions (M-dwarfs and brown-dwarfs), fitting the best parameters. We expect some more interesting results, other than the few new planets that we have found, which are still being analysed, along with hundreds of eclipsing binary stars, for which we have radial velocities.

The first planet OGLE-TR-182-b

After the first year, we had discarded several candidates, but we also had tentative orbits for three planet candidates. These good ones, however, did not have enough velocities to exclude random radial velocity fluctuations as the cause of the orbital signal. In addition, the ephemeris was not confirmed by the photometry: there was a slight discrepancy, which required collection of more data to resolve. Then we started the year 2007, full of hopes about these three objects. Below we tell the story of the first two.

The masses and radii of the stars were not accurately measured, and therefore we could not estimate precisely the masses and radii of our good planet candidates. We again asked ESO to allow a change in strategy, swapping a few hours of FORS time into UVES time in order to get high S/N echelle spectra of a couple of stars to confirm that they are main-sequence stars and to measure their parameters (temperature, gravity, luminosity, and chemical abundances). ESO kindly and quickly approved our change, which allowed us to measure the stellar mass, M = 1.14 +/– 0.05 $M_\odot$, and radius, R = 1.14 + 0.23 – 0.06 $R_\odot$.

The main effort has been devoted to obtaining the ephemeris, which for the two most promising candidates has proven to be difficult. In one case we suspect that we missed the transit because it was observed during the flat bottom portion before the observations ended, and in another case we just caught the ingress, but we observed a full transit on 19 June 2007 (Figure 3).

Finally, we succeeded in confirming candidate OGLE-TR-182-b as a planet, in a paper that also contains analysis of OGLE-TR-178 to TR-200 (Pont et al., 2008). In Figure 4 we show the fit to the OGLE-TR-182 radial velocities obtained with P = 3.9789 days. This object was very difficult to confirm because the period is almost a multiple of one day. Table 2 summarises the derived parameters.

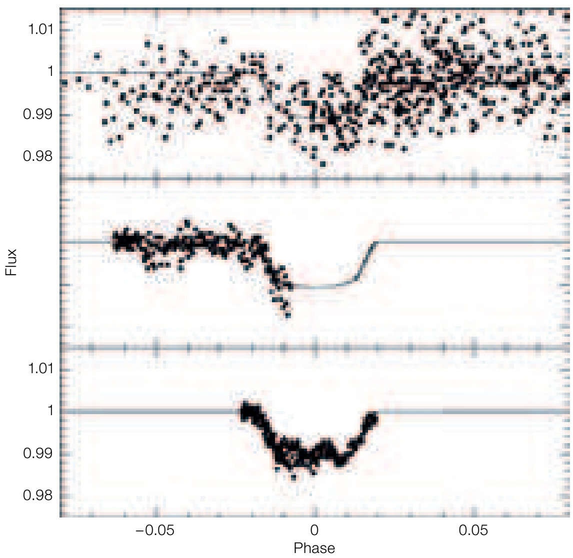

Figure 3. Transit light curves for OGLE-TR-182 from OGLE (top panel), and FORS1 for the nights of 6 June (middle panel), and 9 June 2007 (bottom panel).

Planet ID	OGLE-TR-182-b	OGLE-TR-211-b
Period (days)	3.97910 +/– 0.00001	3.67724 +/– 0.00003
Transit epoch (JD)	2454270.572 +/– 0.002	2453428.334 +/– 0.003
RV semi-amplitude (m/s)	120 +/– 17	82 +/– 16
Semi-major axis (AU)	0.051 +/– 0.001	0.051 +/– 0.001
Radius ratio with primary	0.102 +/– 0.004	0.085 +/– 0.004
Orbital inclination angle	85.7 +/– 0.3	> 82.7
Planet Radius (R_J)	1.13 (+ 0.4 – 0.06)	1.36 (+ 0.18 – 0.09)
Planet Mass (M_J)	1.01 +/– 0.15	1.03 +/– 0.20

Table 2. Measured parameters for the new planets.

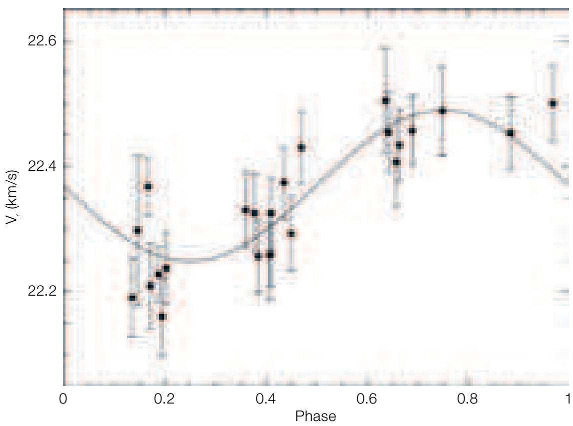

Figure 4. Radial velocity curve for OGLE-TR-182 measured with FLAMES, phased with the photometric transit signal.

The second planet OGLE-TR-211-b

The second planet was not easier to confirm, but we managed to conclude that OGLE-TR-211 is also a planet, in a paper that contains the analysis of candidates OGLE-TR-201 to OGLE-TR-219 (Udalski et al., 2008). Again, we used UVES to determine the stellar parameters: mass M = 1.33 +/– 0.05 $M_\odot$, and radius R = 1.64 + 0.21 – 0.07 $M_\odot$. Figure 5 shows the FLAMES orbital fit for OGLE-TR-211 obtained with a radial velocity amplitude of 82 m/s and period P = 3.67718 days. It can be seen that the velocity curve is very well sampled, from which we measure a planetary mass of M = 1.0 $M_{Jupiter}$.

The photometric transit measured with FORS (Figure 6) gives a radius of R = 1.36 R_J (see Table 2). This radius is about 20 % larger than the typical radius of

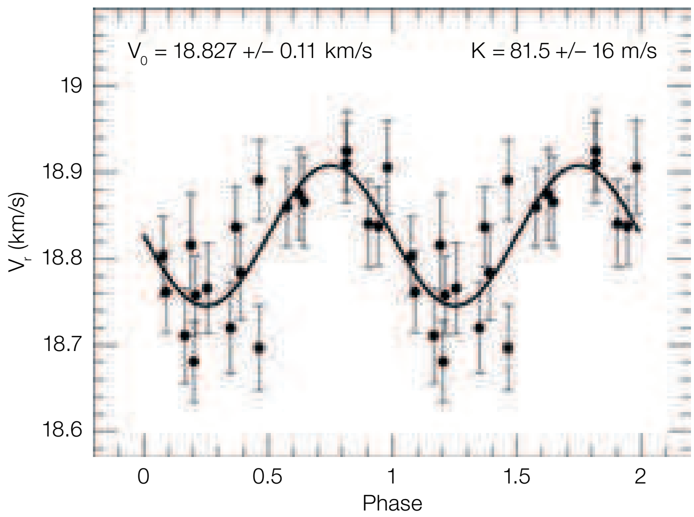

Figure 5. Radial velocity curve for OGLE-TR-211 measured with FLAMES.

hot Jupiters with similar masses. Indeed, this new planet seems to be one of the rare examples of an inflated hot Jupiter, with an unusually low mean density, like HD 209458b. In this case there is some evidence that the velocity of the centre of the mass of the star-planet orbit is changing. Also, slight variations of transit times lead us to suspect that there may be another massive planet in the system that may be perturbing the orbit, but only future observations can confirm if this is real (e.g. due to a companion in the system), or to an instrumental artefact.

Lessons learned

We discovered two new planets! We can now tell with certainty that they are gaseous planets like Jupiter and Saturn, and not rocky like Earth or Venus, nor mostly liquid like Uranus or Neptune. Transiting planets are the only way to get information about their internal structure (and therefore mechanism of formation). Despite the scarce number of such planets, the number starts to be large enough to reveal interesting features. For example, it seems that in order to explain the observed radii, one needs to add a certain quantity of metals in the form of a solid core. It turns out that the mass of this solid core is proportional to the metallicity of the parent star. This trend supports the mode of formation via core accretion (Guillot et al., 2006). However it seems that metallicity is not the only parameter controlling the size of these giant planets, since there are inflated planets around metal rich stars (Torres et al., 2008). The issue is clearly not settled and, in this sense, every new planet counts.

The question can be asked if it isn't more efficient to have a space mission like COROT that focuses on brighter targets? Aside from the obvious answer that a space mission is much more risky and expensive, the LP666 programme, and the observations carried out prior to it, helped the whole team to gain enormously in experience. The team learned how to obtain milli-magnitude photometry, and more importantly, to understand the systematics involved in these kinds of observations (e.g. the red-noise – Pont, 2006). This understanding led to a better (more realistic) prediction of the space mission yields.

In terms of spectroscopic follow-up we learned how to identify the signatures of impostors in an efficient way, and that the candidates that cannot be observed spectroscopically will remain candidates. In particular, we pushed to the limit the FLAMES radial velocity capabilities, and after careful characterisation of these radial velocities, found a precision around 30–50 m/s. More recently, we understood why these two (or three) planets required so much time to be confirmed. They lay in a place that we called the *Twilight Zone* (Pont et al., 2008). When both the photometric and spectroscopic signals are marginal, many more observations are necessary until reasonable certainty can be achieved about the presence of a planetary companion. The uncertainties on the light curve make it difficult to phase the radial velocity data. The high radial velocity uncertainties hinder the identification of an orbital motion with the correct period, and the elimination of eclipsing binary blend scenarios. The OGLE survey is the first to explore this 'twilight zone' in real conditions, since other ground-based surveys target brighter stars, for which very precise radial velocities can be obtained, so that the significance of the radial velocity signal can be established relatively easily. All this *savoir-faire* is already being used in the COROT mission, and would again be useful when the KEPLER mission flies.

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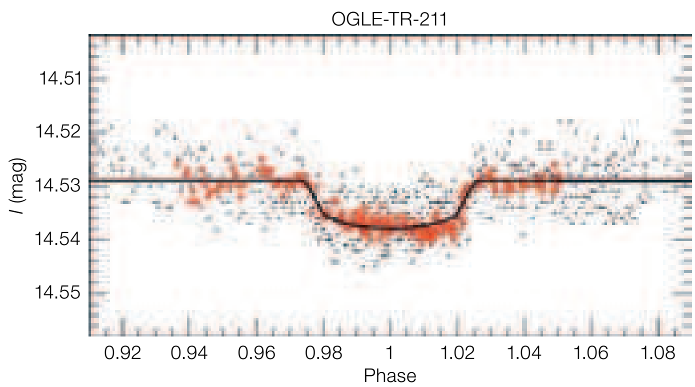

Figure 6. Light curve of the transit of OGLE-TR-211 measured with FORS2.