Transiting extra-solar planets, follow the FLAMES ...

The past year witnessed a blossoming in the field of transiting exoplanets. Until 2003, only one transiting exoplanet was known, the famous HD 209568, first detected by radial-velocity surveys. Then in quick succession, six transiting planets were discovered among the candidates identified by photometric transit surveys. Five of these transiting exoplanets were characterized by our team with FLAMES on the VLT.

Frédéric Pont[1], François Bouchy[2], Didier Queloz[1], Claudio Melo[3], Nuno Santos[4], Stephane Udry[1], Michel Mayor[1], Claire Moutou[2]

[1]Observatoire de Genève, Switzerland;
[2]Laboratoire d'Astrophysique de Marseille, France; [3]ESO
[4]Centro de Astronomia e Astrofísica da Universidade de Lisboa, Observatório Astronómico de Lisboa, Portugal

The orbits of some extra-solar planets intersect the line of sight between the star and the observer, blocking part of the star's light and producing a detectable photometric transit. The probability to have such a geometry is about 10 % for short-period companions. After the first discoveries of planets on short orbits (often called "hot Jupiters") many ground-based surveys have been initiated to search for transit signatures from these hot planets.

Transiting planets are especially precious to study the structure and the evolution of extra-solar planets because the transit signal offers a unique way to measure directly the radius of the planet. If the transit signal can be combined with radial-velocity measurements, a direct measurement of the mass of the planet is obtained as well, the usual sin(i) uncertainty being removed by the edge-on inclination of the orbit. With both the mass and radius measured, the planet mean density becomes known. This allows us to "flesh in" exoplanets in much more detail than for the planets without transit, for which only an estimate of the minimum mass (M sin$i$) is available.

Since 2002 many transiting extra-solar planet candidates were identified as a result of the OGLE survey. To follow up on those announcements, we decided to start a systematic survey of all OGLE candidates. Using ESO facilities and in particular FLAMES on the VLT, we conducted intensive spectroscopic follow-up observations to detect the radial-velocity signatures of announced planet transit candidates, with the objective of assessing their planetary nature by measuring their mass. FLAMES is a multi-fibre link to the UVES and GIRAFFE spectrographs on the VLT.

In a previous Messenger article (June 2004) we presented the detection of the planets OGLE-TR-113b and OGLE-TR-132b that we made with FLAMES. In this article we summarize our whole campaign including the detection of two more planets (OGLE-TR-10b and OGLE-TR-111b). Complete details on this campaign may be found in a series of articles (Bouchy et al. 2004, 2005; Moutou et al. 2004; Pont et al. 2004, 2005, 2005b).

The main outcome of our FLAMES campaign is the identification and the measurement of four true planetary transits, but also the measurement of the mass of many transiting low-mass stellar companions initially tagged as possible planetary transit. Considering the stringent requirements needed to carry out this programme on both the accuracy of the radial velocity and the need for high efficiency to quickly survey a large number of faint objects, we enthusiastically report the unrivalled efficiency of FLAMES/UVES to carry out such a programme. This facility demonstrated that the apparent disadvantage of targeting faint planetary transit candidates can be compensated by their compact location on the sky that allow to benefit from the full multiplexing capability of FLAMES.

At present, seven transiting planets are known (see Table 1). If we look carefully, these measurements are puzzling in various respects. HD 209458 is almost three times less dense than Jupiter, a characteristic that is not yet understood. Three of the OGLE planets (OGLE-TR-56b, 113b and 132b) have periods around 1.5 days, much shorter than the lower limit detected by Doppler surveys of around 3 days, revealing a new class of "very hot Jupiter" (i.e. gas giants even closer to their star than the "hot Jupiters" with periods above 3 days). All three of these objects are also heavier than normal hot Jupiters. OGLE-TR-10b, OGLE-TR-111b and TrES-1 are more typical hot Jupiters, resembling those found in abundance by radial-velocity searches. They have radii ranging from Jupiter size to the anomalous HD 209458, showing that the density of hot Jupiters can vary even under similar orbital conditions.

Table 1: The seven presently known transiting exoplanets and the instrumentation used to measure their radial-velocity orbit – HIRES on the Keck telescope in Hawaii, ELODIE on the 1.93-m at Haute-Provence Observatory, and FLAMES on the VLT.

	Period [days]	Mass [M_J]	Radius [R_J]	Instrument for spectroscopy
OGLE-TR-56	1.21	1.45 ± 0.23	1.23 ± 0.16	HIRES
OGLE-TR-113	1.43	1.35 ± 0.22	1.08 ± 0.06	FLAMES
OGLE-TR-132	1.69	1.19 ± 0.13	1.13 ± 0.08	FLAMES
TrES-1	3.03	0.76 ± 0.05	1.04 ± 0.07	HIRES
OGLE-TR-10	3.10	0.57 ± 0.12	1.24 ± 0.09	FLAMES/HIRES
HD 209458	3.52	0.69 ± 0.02	1.42 ± 0.12	HIRES/ELODIE
OGLE-TR-111	4.02	0.53 ± 0.11	1.00 ± 0.09	FLAMES

The mass-radius diagram of exoplanets constitutes the main outcome of follow-up campaigns on transiting planet candidates (Figure 1). It has already spurred many studies attempting to relate the observed sizes and densities to the incoming stellar flux, the tidal effects and the presence or absence of a rocky core.

The OGLE transit survey

OGLE (Optical Gravitational Lensing Experiment) was originally conceived as a microlensing survey in the Galaxy and towards the Magellanic Clouds. Beginning in 2001, the OGLE team started a survey for transiting planets, using the wide-field camera on the 1.3-m Warsaw telescope at Las Campanas in Chile. Fields in the Galactic disc were observed every season, providing 64 transiting candidates towards the Galactic bulge from the 2001–2002 season, 73 from the 2002–2003 season in Carina, 40 from the 2003–2004 season in Centaurus and Musca (Udalski et al. 2002ab, 2005). Photometric accuracies below 1 % are obtained for up to 100 000 objects in each season, allowing the detection of transit signals of depth from a few per cent down to slightly below one per cent.

Dozens of ground-based planet transit searches are currently under way, but the OGLE survey is dominating the scene. This is probably the consequence of an adequate combination of continuous observation with a 1-m-class telescope equipped with a large detector (8 k × 8 k) and long experience of the team in stable photometric reductions. Most other surveys either rely on very small telescopes covering large fields of several square degrees, or larger telescopes available only during a very limited time.

Our FLAMES follow-up of OGLE transiting candidates

The OGLE survey provided more than one hundred planetary transit candidates, but we found that most of these transits are in fact eclipsing binaries. The measurements of the orbital motion are therefore essential to determine whether the transiting object is a star or a planet. The OGLE targets are between 15 and 18 in V magnitude, and typical planetary orbits cause velocity variations of the order of 100 m/s or lower. The observational challenge posed by the OGLE follow-up is therefore to obtain radial velocities more precise than 100 m/s for objects down to 18th magnitude in V.

In 2002, before FLAMES was available, we attempted to measure a few of the most promising OGLE candidates both with UVES in regular slit mode and with HARPS. Due to the faintness of the targets, the signal-to-noise per pixel in HARPS spectra was often rather low, causing a radial-velocity uncertainty higher than 100 m/s due to photon noise. With UVES in slit mode, enough photons can be collected to compute accurate radial velocities, but we were faced with the problem of uncertainties related to the centring of the star in the slit, that prevented us from obtaining a radial velocity with an accuracy better than 100 m/s. When FLAMES became available, the fibre scrambling effect on the incoming light from the target solved the centring problems and made our follow-up programme feasible, with the additional benefit of multiplexing (the ability to observe seven targets simultaneously with the FLAMES link on UVES).

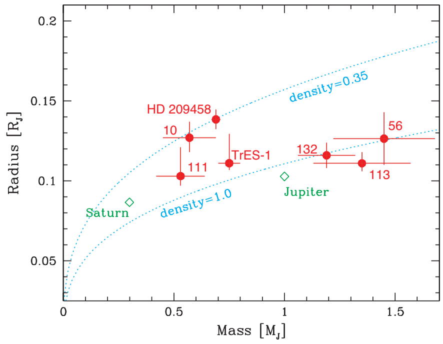

Figure 1: The mass-radius relation for the seven known transiting extra-solar planets.

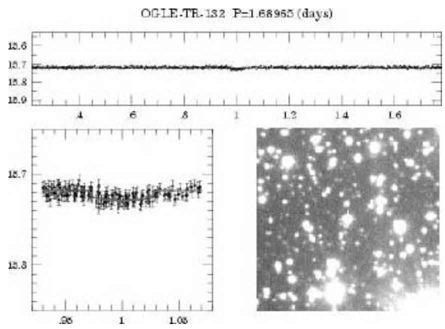

Figure 2: Complete light curve, zoom on the transit, and finding chart for one OGLE candidate, OGLE-TR-132. Planets produce shallow transits that require a high photometric accuracy and long-term stability. This can be difficult to achieve in crowded fields. OGLE-TR-132 is a candidate very near the detection threshold of ground-based surveys that was found to harbour a planet.

In 2003 and 2004, we resolved the nature of 60 OGLE transiting candidates in just eight nights with FLAMES and we found four planets. A mean rate of two nights per planet is about ten times more efficient than radial-velocity survey programmes! Regular radial-velocity survey programmes use typically one night per target through the duration of the survey, and one planet is detected out of 20 targets on average, meaning that about 20 nights are spent to get one planet. This large difference of efficiency reflects the benefit of the multiplex advantage provided by the FLAMES fibre link, and of course the benefit of the previous photometric transit survey.

To optimize telescope use, we have also opted to react in real-time during the observations. During the eight nights of the campaign we analyzed our spectra on the fly, so that we could re-allocate one of the seven FLAMES fibre links to another candidate as soon as we had enough information to identify the transiting body as a stellar companion.

Thanks to the fibre link, we could reduce the systematics in the radial-velocity measurements to less than 30 m/s. When this systematic error is combined with the photon noise error, we are reaching typical accuracies of 40–60 m/s on each individual radial-velocity measurement. Measurements with such errors would be too large to search for a planet without prior information, but in the case of transiting candidates, the orbital period and phase are known from the photometric transit signals, so that such measurements are sufficient to constrain the orbital motion of a planetary companion and measure its mass accurately.

Supporting actors in the OGLE planet follow-up: UVES and FORS

Although the main actor in our spectroscopic follow-up is doubtlessly FLAMES/UVES, there are other supporting actors in this movie. The first of them is FORS.

The shape and depth of a transit light curve are related to the size of the transiting companion, but in some cases, such as OGLE-TR-132, the transit depth is so near to the detection limit that little information can be obtained on its actual shape (see Figure 2). In such cases, FORS can be used to obtain a much better light curve, leading to improved mass and radius determination. That is what we have done for OGLE-TR-132 (see Figure 3). With the benefits of the UT aperture, the quality of the FORS camera and the good seeing of Paranal, we measured the transit shape at the milli-magnitude level, an

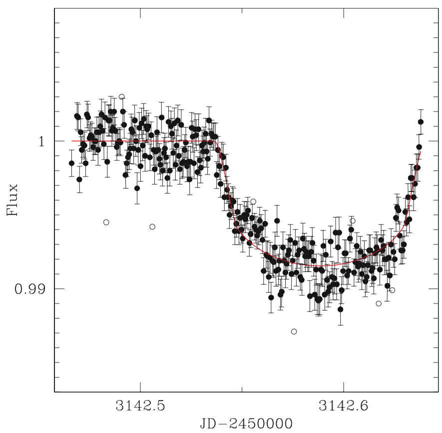

Figure 3: Light curve of the transit of OGLE-TR-132 with FORS2. To be compared with the OGLE detection light curve on Figure 2. Individual errors and systematics are near the level of 1 millimag.

achievement comparable to space performance for such a faint object.

In order to measure the mass and radius of the transiting body, one needs to have an indication of the mass and radius of the primary star. In order to do so, high signal-to-noise stellar spectra (S/N about 100) are needed. Most of our spectra collected with FLAMES/UVES have a S/N that is too low to carry out a precise spectroscopic analysis (although they are good to have precise radial velocities!). UVES in slit mode can be used to collect higher S/N spectra, refining the previous determination of masses and radii for the primary and its companion.

The mass-radius diagram from stars to planets

The main product of our spectroscopic follow-up with FLAMES is of course the characterization of the five planets described above. But another important result was the characterization of 55 candidates that were not planets. This yielded two important by-products:

- Mass and radius for several very low-mass stars, down to the Hydrogen-burning limit.
- A complete image of the range of configurations that can be confused with planetary transits.

Our follow-up of the OGLE candidates has yielded a very rich wealth of empirical information in the mass-radius plots for low-mass stars and planets (Figure 4), comparable to all other previous studies combined.

Two very small stellar objects are particularly interesting: OGLE-TR-122 and OGLE-TR-123. With masses near the Hydrogen-burning limit and radii comparable to that of the hot Jupiters, they provide an observational confirmation of the theoretical prediction that stellar radii reach down to about 0.1 $R_{\odot}$ before entering the regime of a degenerate equation-of-state. These objects also confirm that in some cases it is not possible to distinguish a hot Jupiter transit from a stellar transit from the photometry alone, and that small stellar companions occur at frequencies comparable to hot Jupiters (see Figure 5). This is a major source of concern for very deep transit surveys (such as with the HST), were spectroscopic confirmation is not possible.

FLAMES ahead

The combination of 8-m-class telescope, fibre-feed, high resolution, simultaneous Thorium calibration, and multiplex capacity, puts FLAMES/UVES in a league of its own for the follow-up of deep transit surveys. No other facility in the world combines both the faint multi-object capability and the capacity to measure accurate radial-velocity.

Specialized radial-velocity spectrographs on smaller telescopes, such as HARPS on the ESO 3.6-m at La Silla, can reach a higher absolute precision, but most OGLE targets are too faint and the photon noise on the velocity exceeds the amplitude of a typical planetary orbit. Slit spectrographs on 8-m or 10-m class telescopes (UVES, HIRES) can collect the necessary S/N ratio to push the photon noise low enough, but only at the cost of large systematic uncertainties due to the centring of the object in the slit. The use of an Iodine cell can solve this problem, but only at the cost of losing transmission efficiency and most of the spectral range, so that again the photon noise becomes too large. As a result, even if it had a single fibre, FLAMES is the only facility able to derive a planetary orbit in five measurements for an object such as OGLE-TR-132. Adding to that, the 7-fiber multiplex capacity makes it the king of the jungle for transit follow-up of faint targets.

Figure 6 presents a graphic comparison of the capacity of some facilities for radial-velocity follow-up of faint planetary candidates. This diagram shows that FLAMES is the most performing facility in the relevant range – even before taking into account the multiplex facility that allows several targets to be followed at once! With FLAMES in conjunction with the results from transit surveys, ESO instrumentation has demonstrated its capability to make a major contribution to the empirical knowledge of the mass-radius relation for planets, brown dwarfs and low-mass stars.

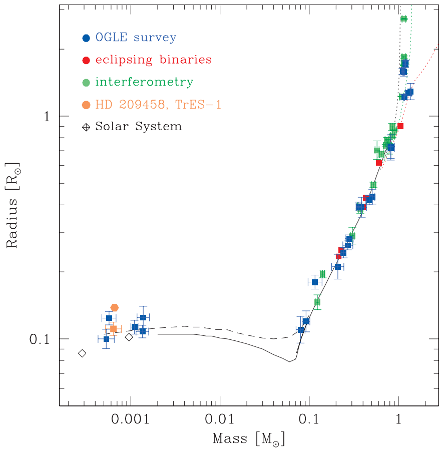

Figure 4 (left): The mass-radius diagram from stars to planets, showing the objects from our follow-up of the OGLE survey, solar-system gas giants, bright transiting planets, bright eclipsing binaries, and stars with interferometric radius determinations.

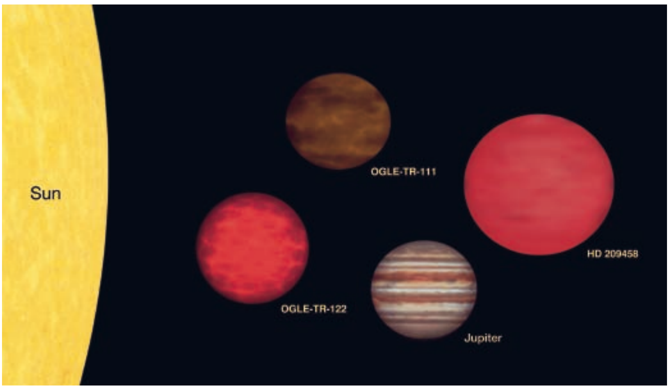

Figure 5 (below): Two stars and three planets... The transiting stellar companion OGLE-TR-122b has a size comparable to Jupiter, and is smaller than the planet HD 209458b. It produces a transit light curve indistinguishable from a planetary transit.

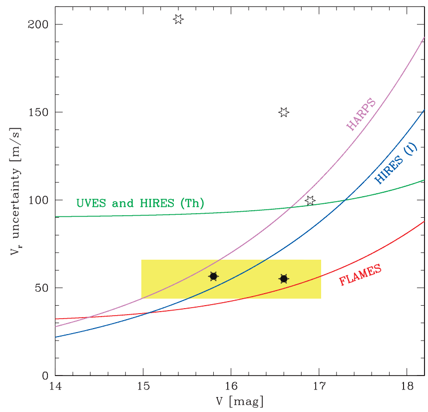

Figure 6 (left): Radial-velocity accuracy versus target magnitudes for different facilities used in the follow-up of faint transiting candidates: FLAMES/UVES on the VLT, UVES in slit mode, HARPS on the ESO 3.6-m, HIRES on the Keck Telescope in Hawaii with a Thorium calibration (Th) or an Iodine cell (I). The stars indicate the velocity dispersion due to orbital motion for detected transiting planets, normal hot Jupiters in black and "very hot Jupiters" in white. The yellow band shows the zone most relevant for the detection of normal hot Jupiters in the OGLE survey.

Acknowledgements

We wish to express our gratitude to all persons that participate in the development of the UVES FLAMES link, making available to the ESO community such a unique and unrivalled facility.

References

Bouchy et al. 2004, A&A Letters 421, L13
Moutou et al. 2004, A&A Letters 424, L31
Pont et al. 2004, A&A Letters 426, L15
Bouchy et al. 2005, A&A 431, 1105
Pont et al. 2005, A&A Letters 433, 21
Pont et al. 2005, A&A, in press, astro-ph/0501615