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Exoplanet detection via microlensing with RoboNet-1.0

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Abstract

RoboNet-1.0 is a prototype global network of three two-meter robotic telescopes, placed in La Palma (Canary Islands), Maui (Hawaii), and Siding Spring (Australia). In April 2004, funding for RoboNet-1.0 until July 2007 was approved by PPARC's Science Committee, and the project commenced in earnest in August 2004. The search for cool extra-solar planets by optimised robotic monitoring of Galactic microlensing events is one of the two core elements of its scientific programme—observations of gamma-ray bursts is the other. During the 2005 observing season, light curves of more than 60 microlensing events have been sampled at regular intervals. One particular event, OGLE-2005-BLG-71, showed an anomaly caused by an extrasolar planet, which constituted the second detection of a planet by microlensing. As a by-product, our dense monitoring during caustic crossing events can resolve the brightness profile of observed source stars, providing an observational test of stellar atmosphere models.

Current development work uses e-science to create a fully automated chain linking event monitoring to the detection of anomalies in the microlensing lightcurves that could be indications of planetary companions and on to the triggering of follow-up observations. In order to fully exploit the potential of such a network for detecting exoplanets, it will be necessary to complement the existing RoboNet with additional telescopes in the southern hemisphere.

Keywords: Experimental techniques; Extrasolar planets; Instrumentation photometry

1. Introduction

The field of time-domain astrophysics, i.e. the investigation of astronomical objects that are variable in flux or position, has greatly benefited from the advent of large robotic telescopes that allow flexible scheduling. The Liverpool Telescope (LT) in La Palma has a mirror diameter of 2 m and can change an instrument at its Cassegrain focus via a rotating mirror within 30 s. This makes it perfectly suited to quickly react on targets of opportunity. Besides, it has the ability to monitor variable objects on time-scales from seconds to years and to schedule observations at a fixed time, e.g. in order to make simultaneous measurements with another facility at different wavelengths (Steele, 2001).

Obviously, a specific request for observation can only be executed by a ground-based telescope at visible wavelengths during nighttime and good weather. Therefore, the flexibility in scheduling can be greatly improved by establishing a network of identical telescopes with very similar instrumentation, but widely separated in latitude and longitude. This goal has been met by RoboNet-1.0,[1] a prototype project that complements the LT with the almost identical Faulkes telescopes in Maui (FTN) and New South Wales (FTS).[2] From now on we use "RoboNet" for short.

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[1] `http://www.astro.livjm.ac.uk/RoboNet/`

[2] In 2005, Las Cumbres Observatory (LCO) has become the owner of the Faulkes Telescopes, designed and built by Telescope Technologies

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The main scientific aims of RoboNet are the determination of the nature of gamma-ray bursts, which requires quick reaction, and the detection of *cool* extra-solar planets, which requires optimised robotic monitoring. By measuring the light curves of galactic microlensing events quasi-continuously, i.e. with sampling intervals of a few hours or even a few minutes, one can detect anomalies that are caused by the presence of a planetary or stellar companion to the lens star. The first exoplanet detected with this technique is OGLE-2003-BLG-235/MOA-2003-BLG-53, determined to be about 1.5 times as massive as Jupiter and orbiting its host star at a transverse separation of 3 AU (Bond et al., 2004).

In the following sections we describe the observations and their results from the first full observing season, April–September 2005, of the RoboNet microlensing planet search.

2. The microlensing method

Liebes mentioned the perturbation of the lens action by planetary deflectors already in 1964 (Liebes, 1964), but Mao and Paczyński (1991) were the first to discuss how planets around a star, that itself causes a microlensing event on an observed background source star, can reveal their existence by creating a deviation in the observed light curve. According to general relativity, light rays originating from a source star at distance D_S are bent due to the gravitational field of an intervening lens star with mass M at distance D_L. This produces two unresolved images, different in shape and size, and therefore in luminosity, from the intrinsic source. For the lens and source star being separated by the angle $u\theta_E$, where

$$\theta_E = \sqrt{\frac{4GM}{c^2}\left(D_L^{-1} - D_S^{-1}\right)} \tag{1}$$

(G is the gravitational constant and c the speed of light) denotes the *angular Einstein radius*, the combined luminosity of the images yields the magnification (Paczyński, 1986)

$$A(u) = \frac{u^2+2}{u\sqrt{u^2+4}}. \tag{2}$$

With a relative proper motion μ between lens and source star,

$$u(t) = \sqrt{u_0^2 + \left(\frac{t-t_0}{t_E}\right)^2}, \tag{3}$$

so that the impact parameter u_0, the time of closest impact t_0, and the event time-scale $t_E = \theta_E/\mu$ parametrise the observed light curve, which is symmetric with respect to t_0. Since $A(u)$ decreases monotonically with u, the magnification reaches its maximum at $A_0 = A(u_0)$, while $A(u) \simeq u^{-1}$ for $u \ll 1$.

Unlike all other methods for detecting extrasolar planets, which favour nearby systems, the parent stars of microlensing planets are at several kpc distance and most ($\approx \frac{2}{3}$) belong to the Galactic bulge rather than the disk population. This is because surveys like OGLE[3] (Optical Gravitational Lensing Experiment) and MOA[4] (Microlensing Observations in Astrophysics) are performed in the Galactic bulge region, where the star density is sufficiently high to make the observation of hundreds of candidate microlensing events per season possible (Wozniak et al., 2001). For typical distances $D_S \approx 8.5\,\mathrm{kpc}$ and $D_L \approx 6.5\,\mathrm{kpc}$, one finds

$$\theta_E \approx 600(M/M_\odot)^{1/2}\ \mu\mathrm{arcsec}, \tag{4}$$

and with a proper motion $\mu \approx 15\,\mu\mathrm{arcsec\,d^{-1}}$, the event time-scale becomes

$$t_E \approx 40(M/M_\odot)^{1/2}\ \mathrm{days}. \tag{5}$$

Fainter lens stars are more common, and by causing a smaller reduction of the observed magnification by contributing blended light, they are further favoured compared to brighter ones. However, the probability for a lens star to cause a microlensing event increases with $\sqrt{M}$. As a result, microlensing events are most likely caused by M-dwarfs. For a typical lens star with $M \approx 0.3M_\odot$, the event therefore lasts about a month, whereas deviations by planets last from a few days for Jupiters to a few hours for Earths.

The effect of a planet around the lens star on the apparent brightness of the observed source star is described by only two parameters, the planet-to-star mass ratio q and the dimensionless separation d, where $d\theta_E$ is the instantaneous angular separation. With the duration of the planetary signal being much smaller than the orbital period, one obtains a "snapshot", while the orientation and phase of the orbit as well as its eccentricity is not measured.

The gravitational field of the parent star increases the planet detection efficiency, so that it reaches a maximum for an angular separation that equals the angular Einstein radius. As a region of large detection efficiency, one commonly defines the *lensing zone* as the range $0.6 \leqslant d \leqslant 1.6$, being a favoured range of separations. Based on the typical values, an uncertainty factor of 2 on θ_E, and a deprojection of the orbit, this roughly translates to semi-major axes $0.8\mathrm{AU} \leqslant a \leqslant 9\mathrm{AU}$, while there is still some substantial sensitivity for planets within twice this lensing-zone limit.

As long as the source stars can be regarded as point-like, less massive planets can provide signals of the same amplitude as more massive counterparts, albeit with a smaller probability. While for giant planets, the finite size

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(*footnote continued*)
Limited, from the Dill Faulkes Educational Foundation, which became the educational arm of LCO.

[3] `http://www.astrouw.edu.pl/~ogle/`

[4] `http://www.physics.auckland.ac.nz/moa/`

of Galactic bulge stars can be neglected, the planetary signal is strongly affected for observed giants if planets below 10 Earth masses are considered, and the size of main-sequence stars places a limit on the detectability around Earth mass, assuming a 1% photometric accuracy for ground-based campaigns. However, this leaves microlensing as the only technique currently capable of detecting Earth-like planets.

In general, events with larger peak magnifications have larger planet detection efficiencies. The probability to detect a Jupiter-mass planet in the lensing zone among events with $A_0 \geqslant 2$ is about 20% (Gould and Loeb, 1992), while for Earth-mass planets (against main-sequence source stars) it is about 1% (Bennett and Rhie, 1996). In contrast, among events with $A_0 \geqslant 10$, Jupiter-mass planets are detected with 95% probability, while a 30% probability still applies to ten-Earth-mass planets and main-sequence source stars (Griest and Safizadeh, 1998). The current event magnification, i.e. magnification at current time, can serve as indicator for the probability that a planetary deviation occurs, whereas brighter targets are favoured by requiring shorter exposures for achieving the same photometric accuracy. Based on this, RoboNet uses a priority algorithm for selecting its targets and dividing the total observing time between the chosen ones. The priority algorithm allocates observing time on each night among all available microlensing events in order to maximise the probability of detecting a new planet. This assumes that planets orbiting the lens stars have randomly oriented orbits and are distributed uniformly in log of separation from the lens star. Each data point defines a detection zone for planets surrounding each of the two images of the source star that are created by the lens star, where a sufficiently massive planet falling inside this zone creates a detectable deviation from the symmetric single-lens light curve. The detection zone area is proportional to the signal-to-noise ratio of the photometric data point, to the planet/star mass ratio q, and to a simple function of the current magnification A of the source star (proportional to $2A-1$ at magnifications $A \geqslant 3$).

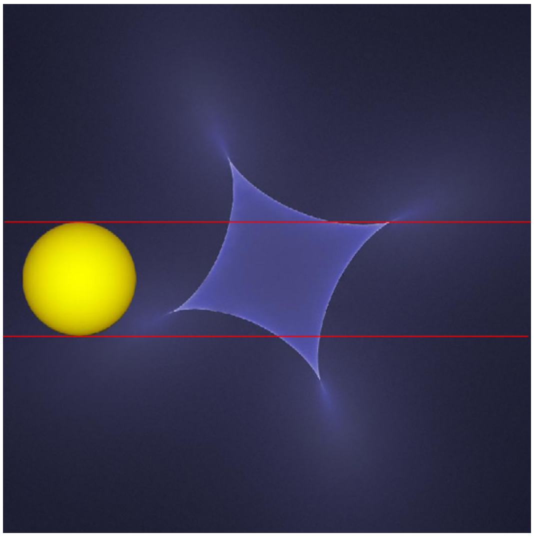

Fig. 1. The caustic curves of the binary lens of event MOA-33 (Rattenbury et al., 2005). The source star (yellow), shown to scale, has a relative motion horizontally from left to right. The circular source star profile is shown close to the moment of the caustic entry, corresponding to rapid changes in magnification. The caustic curve covers different regions of the source star at different times.

Whenever the finite size of the source star affects the light curve, the stellar brightness profile can in principle be measured. In particular, the star exhibits a strong differential magnification across its face if a caustic, produced by the gravitational field of the lens, including stellar binaries and planetary systems, is transited (see Fig. 1). With caustic transits lasting between a few hours and a few days, we can easily obtain a few hundred data points over the diameter of the star in these cases, which allows the determination of limb-darkening coefficients and is one of the few available observational tests of stellar atmosphere models (Albrow et al., 2001; Dominik, 2004a).

3. Observations

The first observations with RoboNet took place in 2004, when five hours were spent on the LT and six on the FTN to establish the viability of monitoring microlensing targets far from the zenith. Those were selected from the events detected by OGLE (Udalski et al., 1997, see Table 1), which were publicly announced while in progress. Our

Table 1
Details of the 2004 season

Event	Total t_{exp} on LT (s)	Total t_{exp} on FTN (s)
OB04203	1364	1368
OB04296	0	691
OB04342	0	444
OB04364	2494	2716
OB04383	2434	1455
OB04384	312	1104
OB04398	280	156
OB04402	0	379
OB04407	0	404
OB04432	3788	1543
OB04442	0	900
OB04458	0	304
OB04478	0	976
OB04482	734	925
OB04491	1088	352
OB04496	1256	1012
OB04501	278	0
OB04528	2172	1901
OB04529	122	548
OB04534	146	414
OB04539	0	512
OB04544	0	304
OB04552	0	348
OB04553	0	1432
OB04565	546	0

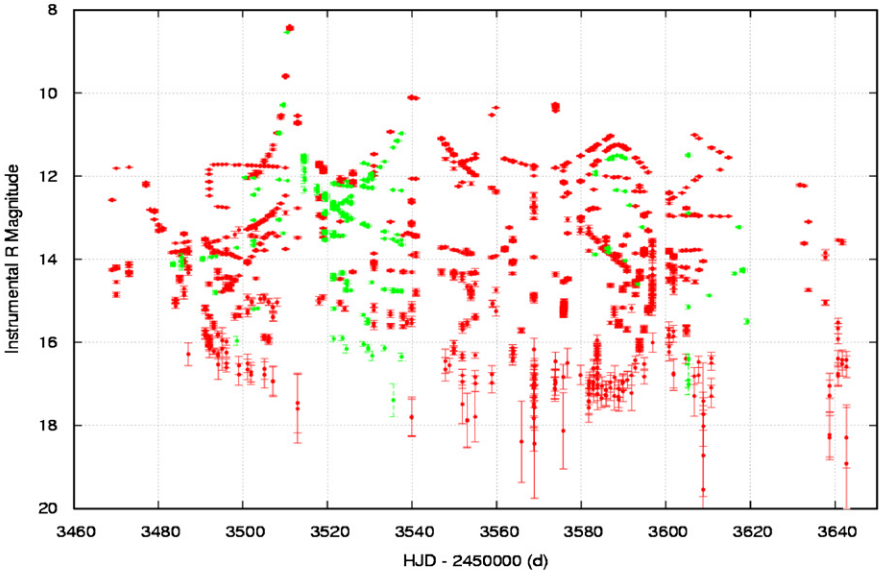

Fig. 2. LT (green) and FTN (red) data points of Galactic Bulge microlens events secured and automatically reduced during the 2005 observing season.

observations already followed an automated system for the prioritisation of targets. The data quality was as good as in later seasons, but the sampling of events was generally incomplete, and many events were only observed on their way down. So the data set was a good test for observing the bulge from northern sites but not much else.

In 2005, the FTS was not ready for service during the microlensing season, therefore, observations could only be performed with LT and FTN, starting with the latter in April. Because of the more northern latitude of La Palma compared to Maui and the slightly higher altitude that a target for LT must have above the horizon to be observable, LT began to point at microlensing events in the Galactic bulge only in May. Our observing strategy followed a hybrid approach: ordinary events were scheduled according to our priority algorithm in order to maximise the probability to detect a planetary anomaly, whereas events identified as anomalous by the PLANET collaboration[5] (Dominik et al., 2002) were intensively monitored—typically with one observation per hour—as long as the anomaly lasted. OGLE found 600 candidate microlensing events in the first 10 months of 2005, from which we had to make our choice. The results of our priority algorithm were updated once per hour—this may increase in later seasons—and placed on a web page.[6] A so-called ''intelligent agent'', namely a computer program responsible for implementing the observations, retrieved the parameters from the web page and entered corresponding observing requests into the scheduler, while the parameters of identified anomalies were entered manually. Subsequently, the scheduler software sent the necessary commands to the respective robotic telescope, unless there was a target-of-opportunity pending, e.g. a gamma-ray burst, which received higher priority.

RoboNet reached in the best cases a photometric accuracy of 0.01 mag RMS (1% accuracy) at R mag $\approx$ 14 and 0.1 mag RMS (10% accuracy) at R mag $\approx$ 17. These figures can depend on the field, but in any case the telescopes are capable of providing reliable photometry even for the weakest sources that were found by OGLE to undergo a microlensing event. Fig. 2 shows the data points of events monitored with the RoboNet telescopes between April and September 2005, for which the source stars were magnified by up to four magnitudes. Over this period, 2652 observations were carried out with FTN and 768 with LT, on a total of 59 or 17 events, respectively.

4. Data processing

The raw data from each observation were first run through the automatic data reduction pipeline,[7] which is the same for all RoboNet telescopes. Its main processing steps consist of bias and dark subtraction as well as flat fielding. Each set of identical exposures is processed by this pipeline before the next one is taken. This enables the telescope to feed for example changes in the seeing conditions promptly back in the scheduling model.

The reduced science frames were then passed into a fully automatic version of the difference imaging pipeline described in Bramich et al. (2005). Difference image analysis (DIA, Alard and Lupton, 1998) attempts to match the point spread function between a best seeing reference frame and the frames in a time-series. A difference image is constructed by subtraction of the reference frame, degraded to the seeing of the current image, from the current

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[5] `http://planet.iap.fr/`

[6] `star-www.st-and.ac.uk/~robonet/2005/micro_events.html`

[7] `http://telescope.livjm.ac.uk/Info/GenInfo/pipeline.html`

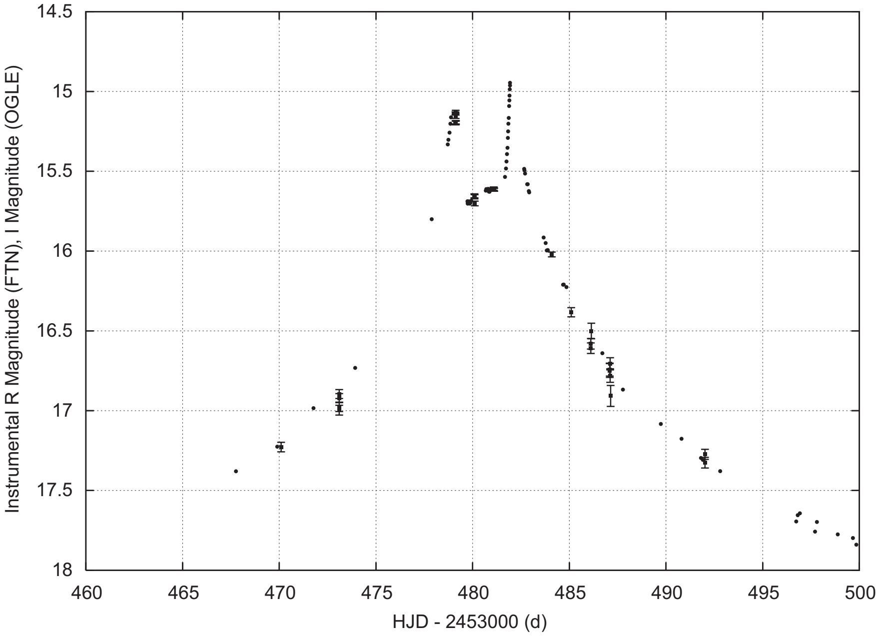

Fig. 3. Observations of OGLE-2005-BLG-071 by the OGLE (filled circles) and RoboNet (filled squares with error bars) telescopes exhibit an anomaly at the top of the light curve as arising from a three-Jupiter mass planet located about 3 AU from the lens star (Udalski et al., 2005).

image. Non-varying stars leave no residual on the difference image, and variables leave either a positive or negative flux with respect to the reference frame. The difference flux is compared to the flux on the reference frame and converted to a magnitude, generating a light-curve.

The automatic DIA pipeline creates a reference frame by aligning and stacking all images with a FWHM within 10% of the FWHM of the best seeing image. Images are not used in the stacked reference frame if they have obvious defects or an unusually high sky background. If a new image becomes available that can be added to the reference frame to improve the signal-to-noise ratio, then the reference frame is recreated, and all difference images and photometry are redone. This processing allows the measurement of changes in the observed flux with high accuracy, while the absolute level is already known from OGLE photometry.

5. Results

5.1. Exoplanets

In May 2005, RoboNet participated in observations that led to the second discovery of a planet by microlensing (Udalski et al., 2005). The light curve for event OGLE-2005-BLG-71, which includes the planetary signal, is shown in Fig. 3, where data from the FTN and the OGLE 1.3 m telescope are displayed. After the OGLE team detected the event in progress by means of the OGLE-III Early-Warning-System (Udalski, 2003) and publicly alerted on this event, RoboNet automatically retrieved the information from the OGLE EWS web page[8] and added it to its priority queue, so that FTN observations were scheduled before other follow-up campaigns were able to react. The μFUN collaboration[9] first recognised an anomaly in this event and alerted other groups, which then intensified their observations. In particular, the event was also monitored by PLANET. RoboNet/FTN observed on three nights during the anomaly—obviously southern telescopes have an advantage here. We were also sensitive to detecting an Earth-mass planet at the same orbital separation, which would have produced an anomaly of similar amplitude, but lasting a few hours rather than days.[10]

The planet detections by microlensing demonstrate our potential for exploring the abundance of cool planets as a function of their mass and orbital semi-major axis or period, rather than facing selection effects in favour of close-in (hot) planets as resulting from the radial-velocity method.

5.2. Stellar atmospheres

During the 2005 season, an excellent candidate for studying stellar atmospheres, namely OGLE-2005-BLG-18, was monitored. It constitutes an unprecedented case in

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[8] `http://www.astrouw.edu.pl/~ogle/ogle3/ews/ews.html`

[9] `http://www.astronomy.ohio-state.edu/~microfun`

[10] While this paper was being refereed, the first cool rocky/icy exoplanet around an ordinary star revealed its existence around the lens star of event OGLE-2005-BLG-390. This result was published as the common product of PLANET/RoboNet, OGLE, and MOA (Beaulieu et al., 2006).

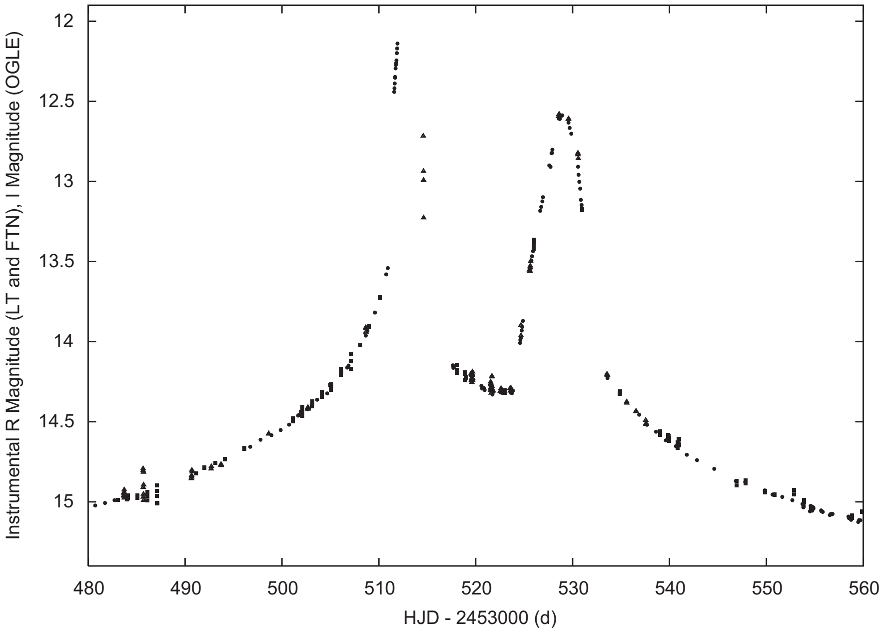

Fig. 4. LT (triangles), FTN (squares), and OGLE (circles) observations of OGLE-2005-BLG-018, involving long-lasting passages of the source over 4 caustic lines, resulting from the gravitational field of a binary lens star.

which the source passed subsequently over 4 caustic lines under different angles. Moreover, each of these passages lasted a few days, allowing a good time resolution for observations in different filters even with modest effort. The scheduling of observations, which started with FTN *before* any anomaly alert was given out, was eased by the fact that real-time modelling by PLANET successfully predicted relevant upcoming features of the light curve. Fig. 4 shows the RoboNet data from both LT and FTN on this event with observations in r' or R, respectively. Detailed modelling of this event is underway.

6. Discussion

By already contributing to the discovery of a new exoplanet in the first full observing season, we demonstrated the usefulness of RoboNet for the search for planets of other stars and determining their abundance as a function of mass and orbital semi-major axis or period. In 2006, the capability of RoboPLANET, the common campaign of the PLANET and RoboNet collaborations, will greatly increase with FTS expected to be able to add up to 10 h to the maximal four hours per night from LT and FTN, and the implementation of a real-time system to detect, confirm, and characterise anomalies.

Long-term, it will become necessary to add southern scopes at more longitudes, i.e. in South Africa or South America, for 24-h robotic coverage in the high-sensitivity search for cool Earths. Obviously, such a project could be combined with other search methods like transit studies or quite different investigations in time-domain astrophysics. An even more ambitious—and far more expensive—project is to use microlensing techniques with a space-based observatory. This could lead to the discovery of order 100 Earth-mass planets (Bennett et al., 2003). Another potential of microlensing lies in its capability for detecting planets around stars in the Andromeda Galaxy (M31), as pointed out by Covone et al. (2000). Contrary to Galactic bulge targets, the source stars themselves remain unresolved, while one observes a variation of the light in a single pixel of the detector, to which many stars contribute. As suggested by Dominik (2002, 2004b), an ongoing observing programme with RoboNet and other telescopes (Angstrom,[11] Principal Investigator: E. Kerins) might be able to yield first detections of such extra-galactic planets (Chung et al., 2005).

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[11] `http://www.astro.livjm.ac.uk/angstrom/`

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