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Detecting planets around stars in nearby galaxies

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Abstract. The only way to detect planets around stars at distances $\gtrsim$ several kpc is by (photometric or astrometric) microlensing (μL) observations. In this paper, we show that the capability of photometric μL extends to the detection of signals caused by planets around stars in nearby galaxies (e.g. M31) and that there is no other method that can achieve this. Due to the large crowding, μL experiments towards M31 can only observe the high-magnification part of a lensing light curve. Therefore, the dominating channel for μL signals by planets is in distortions near the peak of high-magnification events as discussed by Griest & Safizadeh (1998). We calculate the probability to detect planetary anomalies for μL experiments towards M31 and find that jupiter-like planets around stars in M31 can be detected. Though the characterization of the planet(s) involved in this signal will be difficult, the absence of such signals can yield strong constraints on the abundance of jupiter-like planets.

Key words: galaxies: individual: M 31 – cosmology: gravitational lensing – stars: planetary systems

1. Introduction

The existence of 'other worlds' has always been one of the most discussed topics in the history of philosophy and science. The question has fascinated researchers since more than 2000 years, but the first attempt in modern astronomy to discover extrasolar planets was given by Huyghens (1698), in the XVII century. One had to wait nearly another 300 years until the first extrasolar planets have been discovered (Mayor & Queloz 1995; Marcy & Butler 1996), namely by observing the radial velocity of the parent star by Doppler-shift measurements. All of the confirmed detections of extrasolar planets so far result from this technique and ~ 20 planets have been found (Schneider 1999).

Already in 1991, Mao & Paczyński (1991) have pointed out that not only a (dark) foreground star that passes close to the line-of-sight of an observed luminous background source star yields a detectable variation in the observed light of the source star but also a planet around the foreground (lens) star can significantly modify the observed light curve. Gould & Loeb (1992) have shown that there is a significant probability to detect jupiter-mass and saturn-mass planets around stars in the Galactic disk that act as microlenses by magnifying the light of observed stars in the Galactic bulge. Bennett & Rhie (1996) have pointed out that the capability of detecting planets by this photometric microlensing (μL) technique extends to earth-mass planets, where the limit is given by the finite size of the source stars.

Contrary to all techniques employed or suggested to search for planets, photometric μL does not favour nearby objects. This makes it the unique technique to search for planets around stars at distances larger than a few kpc. Moreover, for disk lenses and bulge sources, a separation between planet and parent star of 2–6 AU is favoured, making it an ideal method to look for jupiter-like systems. Since the parent star of the planet acts as a gravitational lens only through its gravitational field, there is no luminosity bias for the parent stars that are generally not even seen. Moreover, it is the only method to discover Earth-like planets from ground-based observations.[1]

Several teams have started to look for planetary anomalies in μL light curves with monitoring programs that perform frequent and precise observations, namely PLANet (Albrow et al. 1998; Dominik et al. 1999), MPS (Rhie et al. 1999), and MOA (Hearnshaw et al. 2000). All these teams rely on the microlensing 'alerts' issued by teams that undertake surveys of $\sim 10^7$ stars: OGLE (Udalski et al. 1997), MACHO[2] (Alcock et al. 1996, 1997), and EROS (Palanque-Delabrouille et al. 1998).

While most of these alerts are on Galactic bulge stars, MACHO and EROS also observe(d) fields towards the Magellanic Clouds. However, the number of events towards SMC and LMC comprises only 5–10% of the total number of events. In addition to detecting planets around stars in the Galactic disk (typically at

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[1] In 1992, Earth mass objects have been discovered around the pulsar PSR1257+12 (Wolszczan & Frail 1992; Wolszczan 1994) through time-delay measurements. The discovery is undoubtful, but the very nature of these objects is completely unknown: it is difficult, at the moment, to conciliate this discovery with our picture of planetary systems. A precise definition of a planet is a subtle question (see Marcy & Butler 1998).

[2] MACHO will discontinue its operation by the end of 1999.

4 kpc distance) one could also think of detecting planets around stars in the Magellanic Clouds (at ~ 50 kpc distance). However, in addition to the relative small number of detected events, finite source effects play a much more prominent role for lensing of stars in the Magellanic Clouds by stars in the Magellanic Clouds than for lensing of Galactic bulge stars by Galactic disk stars (Sahu 1994) resulting in a dramatic decrease in the probability to detect planetary signals.

Safizadeh et al. (1999) have pointed out that planets around disk stars can also be detected by looking at the shift of the light centroid of observed source stars caused by microlensing of disk stars and surrounding planets with upcoming space interferometers that allow to measure astrometric shifts at the μas level. Contrary to photometric μL, the observed signal of this 'astrometric μL' technique decreases with the distance of the lenses (e.g. Dominik & Sahu 1998). With μas-astrometry, jupiter-mass planets can only be detected for distances up to $\lesssim 30$ kpc. This leaves photometric μL as the only method ever capable of detecting planets in nearby galaxies like M31.

In contrast to microlensing observations towards the Galactic bulge and the Magellanic Clouds, a large number of source stars fall onto the same pixel of the detector for observations towards M31. However, it is still possible to detect μL events even in unresolved star fields (Baillon et al. 1993; Gould 1996). Since standard photometric methods cannot be used to reveal μL events, new techniques have been developed: super-pixel photometry (Ansari et al. 1997) and difference image photometry (Tomaney & Crotts 1996; Alard & Lupton 1998). These techniques are used for the μL searches towards M31 as carried out by the Columbia-VATT search (Crotts & Tomaney 1996), AGAPE (Ansari et al. 1997), SLOTT-AGAPE (Bozza et al. 1999), and MEGA (Crotts et al. 1999).

In this paper we investigate the possibility to detect planets around stars in M31 with experiments that make use of either of these techniques. By searching for planets (or, at least, brown dwarfs) even in other galaxies, the limit for planet detection is further pushed towards larger distances.

The paper is organized in the following way: in Sect. 2, we discuss the characteristics of microlensing signals caused by planets. In Sect. 3, the conditions for detecting anomalies in light curves of M31 are discussed. In Sect. 4, we calculate the probability to detect planetary signals in M31, and in Sect. 5, we discuss the extraction of planetary parameters. Finally, in Sect. 6, we summarize and conclude.

2. Microlensing signals of planets

A microlensing event occurs if a massive lens object with mass M located at a distance D_L from the observer passes close to the line-of-sight towards a luminous source star at the distance D_S from the observer. Let u denote the angular separation betwen lens and source in units of the angular Einstein radius

$$\theta_\mathrm{E} = \sqrt{\frac{4GM}{c^2}\,\frac{D_\mathrm{S}-D_\mathrm{L}}{D_\mathrm{L}\,D_\mathrm{S}}}\,. \tag{1}$$

For the 'standard model' of μL, i.e. point-like sources and lenses, the magnification μ is then given by (Paczyński 1986)

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

If one assumes uniform rectilinear motion between lens and source with the relative proper motion μ, one has

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

where $t_\mathrm{E} = \theta_\mathrm{E}/\mu$, u_0 gives the impact parameter, and t_0 gives the time of the smallest separation between lens and source. This means that one observes a light curve $\mu(u(t))$ that has the form derived by Paczyński (1986), the so-called Paczyński curve. For recent and complete reviews of the theory of microlensing and of the observational results we further refer to the works of Paczyński (1996), Roulet & Mollerach (1997), and Jetzer (1998).

More sophisticated models of the lens and the source include the finite source and the binarity (or multiplicity) of these objects. For such models, the light curves can differ significantly from Paczyński curves.

If one neglects the binary motion, a binary lens is characterized by two parameters, the mass ratio between the lens objects q and their instantaneous angular separation d, measured in units of θ_E. The model of a binary lens includes the configuration of a star that is surrounded by a planet. In the following, we let M denote the mass of the more massive object (star), while m denotes the mass of the less massive object (planet) and $q = m/M < 1$. This means that θ_E refers to the mass M of the more massive object.

For any mass ratio q, the caustics of a binary lens can show three different topologies (Schneider & Weiß 1986; Erdl & Schneider 1993) depending on the separation d: For 'wide binaries' there are two disjoint diamond-shaped caustic near the positions of each of the lens objects, for 'intermediate binaries' there is only one caustic with 6 cusps, and for 'close binaries' there is one diamond-shaped caustic near the center-of-mass and two small triangular shaped caustics. As $q \to 0$, the region of intermediate binaries vanishes as $q^{1/3}$ and the transition close-intermediate-wide occurs at $d = 1$ (Dominik 1999). This means that for planets, one has a 'central caustic' near the star and either a diamond-shaped caustic (for $d > 1$) or two triangular shaped caustics (for $d < 1$) at the position that had an image under the lens action of the star, considered at the position of the planet. We will refer to the latter caustic(s) as 'planetary caustic(s)'.

Since the caustics are small and well-separated, the light curve mainly follows a Paczyński curve and is only locally distorted by either of the caustics. This allows us to distinguish two main types of anomalies in the light curve, namely the events affected by the central caustic (type I), and the ones affected by one of the planetary caustics (type II).

To produce a Type I anomaly, the source has to pass the lens star with a small impact parameter, say $u_0 \lesssim 0.1$. Unless the source size is larger than variations in the magnification pattern, type I anomalies occur in high-magnification events ($\mu \simeq 1/u$ for $u \ll 1$). Moreover, the anomaly occurs near the maximum of the underlying Paczyński curve. Griest & Safizadeh (1998) have pointed out that for high-magnification events, the probability to detect a planetary signal, namely as type I anomaly, is very large. In order to produce a high detection probability, the central caustic is often elongated along the lens axis, so that the magnification pattern is highly asymmetric around the lens star. If there are N planets with masses m_i around the parent star with mass M, they all perturbate the central caustic (Gaudi et al. 1998), where the effect is proportional to the mass ratios $q_i = m_i/M$ (Dominik 1999). Though in principle, one can obtain information about the whole planetary system, the extraction of this information is non-trivial and the results are likely to be ambiguous (Dominik & Covone, in preparation).

Type II anomalies are produced when the source passes close enough to the lens to produce a detectable Paczyński curve ($u_0 \lesssim 1$), but not close enough to feel the effects of the central caustic ($u_0 \gtrsim 0.1$), and also gets affected by the planetary caustics, so that the source light beam will also be deflected by the planet, and a perturbation of the Paczyński curve is produced at a time that depends on the angular separation between star and planet. From this time and from the duration of the perturbations, mass ratio q and separation d can be determined from high-quality observations, unless the duration is strongly influenced by the source size (Gaudi & Gould 1997; Dominik & Covone, in preparation).

Experiments towards unresolved star fields in nearby galaxies set very limiting conditions on the detection of μL events in general and on the detection of anomalies in particular. First, only the parts of the light curve that correspond to large magnifications can be observed. Second, anomalies can only be seen when they constitute very large deviations of the received flux. Therefore, all observed events are high-magnification events which gives a lot of candidates to look for type I anomalies. On the other hand, the background Paczyński curve for type II anomalies is not observed, and the planetary caustic has to be approached very closely to produce a high magnification. Therefore, type II anomalies are not likely to be detected in M31 experiments.

Griest & Safizadeh (1998) have studied the influence of the finite source size for type I anomalies. For sources in the Galactic bulge and lenses in the Galactic disk, they find that the finite source size can be neglected even for giant sources ($R \sim 10\ R_\odot$) for a parent star of solar-mass and a mass ratio $q > 10^{-3}$. The characteristic quantity for the effect of the finite source size is the ratio between source size and the physical size of the angular Einstein radius at the position of the source

$$r'_E = D_\mathrm{S}\,\theta_\mathrm{E} = \sqrt{\frac{4GM}{c^2}\,\frac{D_\mathrm{S}\,(D_\mathrm{S}-D_\mathrm{L})}{D_\mathrm{L}}}\,. \tag{4}$$

For lensing of bulge stars by disk stars, $D_\mathrm{S} \sim 8$ kpc and $D_\mathrm{L} \sim D_\mathrm{S}/2$, while for M31 sources and lenses, $D_\mathrm{S} \sim D_\mathrm{L} \sim 600$ kpc and $D_\mathrm{S} - D_\mathrm{L} \sim 10$ kpc. Therefore r'_E is approximately the same in the two cases and the estimates for the effect of the finite source size made for bulge stars and disk lenses are also valid for M31 sources and lenses.

If the finite source size becomes non-negligible, the planetary signal is suppressed. We therefore restrict our discussion to planets with mass ratio $q > 10^{-3}$, i.e. Jupiter-like planets around stars of solar-mass and systems with larger mass ratio.

3. Detectability of anomalies in M31 experiments

For μL searches towards M31, each pixel of the detector contains light from many unresolved stars. There are several differences between classical microlensing surveys (i.e. surveys on resolved stars) and surveys towards unresolved star fields.

The first one concerns the photometric errors. While in the classical regime, the photon noise is generally dominated by the light from the lensed star, it is dominated by the flux from stars that are not lensed for observations towards unresolved star fields. This means that the noise does not depend on the magnification. A second important difference is that it is impossible to determine the baseline flux of the lensed star. This means that the actual magnification and the Einstein time t_E of the event are not known.

Moreover, in surveys towards unresolved star fields, there is a natural selection bias for the events with respect to the impact parameters and the luminosity of the lensed sources (e.g. Kaplan 1998): events that involve lensing of giant stars and events with small impact parameters are preferred.

Searches of μL events towards unresolved star fields (Crotts 1992; Baillon et al. 1993), M31 in particular, have motivated the development of new photometric methods. While the AGAPE team has implemented a ‘super-pixel photometry’ method (Ansari et al. 1997; Kaplan 1998), the Columbia-VATT team has used a ‘difference image photometry’ method (Crotts & Tomaney 1996; Tomaney & Crotts 1996). Recently, Alard & Lupton (1998) have improved the latter method yielding the ‘Optimal image subtraction’ (OIS) technique.

The Columbia-VATT collaboration has found six candidate events towards M31 (Crotts & Tomaney 1996).

AGAPE has observed 7 fields towards M31 in autumns 1994 and 1995, using the 2 meters telescope Bernard Lyot at the Pic du Midi Observatory. Their data analysis has selected 19 microlensing candidate events that are broadly consistent with Paczyński curves. Only two of them can be retained as convincing candidates at the moment (Melchior 1998). One of these events shows a small but statistically significant deviation from a Paczyński curve (Ansari et al. 1999). This event could be due to lensing of a binary source, or even to a binary lens. There are too few data points to resolve the question, and other observations are needed to confirm that the event is due to μL and not due to stellar variability. In any case, the possibility to detect binary lens events towards unresolved star fields has been demonstrated.

This gives us some confidence that future μL searches towards nearby galaxies could not only detect binary-lens events, but also reveal Jupiter-like planets. From a general point of view, we expect a larger fraction of anomalous microlensing events, since smaller impact parameters are favoured so that source trajectories are more likely to pass through the more asymmetric parts of the magnification pattern. However, the less accurate photometry sets a severe limit on the detection of anomalies. In the following, we determine how large an anomaly has to be in order to be detected in an M31 μL experiment.

The light in an observed pixel is composed of contributions from the lensed star and many other unresolved stars. Since the light from the lensed star is in general spread over several pixels, only a fraction f of it is received on a given pixel. If μ denotes the magnification of the lensed star, and $F_{\rm star}^{(0)}$ denotes its unlensed flux, the flux variation on the pixel is given by

$$\Delta F_{\rm pixel} = (\mu - 1) f F_{\rm star}^{(0)}, \tag{5}$$

where μ, f and $F_{\rm star}^{(0)}$ are not observed individually.

Let us now consider an anomaly in an event, i.e. a deviation from a Paczyński curve. Let μ denote the magnification for the Paczyński curve and μ' the magnification for the anomalous curve. The difference in the pixel flux variations is then given by

$$\Delta(\Delta F_{\rm pixel}) = (\mu' - \mu) f F_{\rm star}^{(0)} \,. \tag{6}$$

This difference is detectable when it exceeds the rms fluctuation $\sigma_{\rm pixel}$ by a factor Q, i.e.

$$\mu' - \mu \geq Q \frac{\sigma_{\rm pixel}}{f F_{\rm star}^{(0)}} \,. \tag{7}$$

One sees that the brighter the star the less the magnification variation has to be in order to be detected. Thus, giant stars are preferred as sources.

For $\mu \gg 1$, one obtains a detection threshold $\delta_{\rm th}$ for anomalies with Eq. (5) as

$$\delta_{\rm th} \equiv \left| \frac{\mu' - \mu}{\mu} \right|_{\rm th} = Q \frac{\sigma_{\rm pixel}}{\Delta F_{\rm pixel}} \,. \tag{8}$$

To obtain an estimate, we have a look at the values of $\sigma_{\rm pixel}$ and $(\Delta F_{\rm pixel})_{\max}$, i.e. $\Delta F_{\rm pixel}$ at the maximum, for the 19 candidate events detected by AGAPE and analyzed using the super-pixel photometry technique (Ansari et al. 1997). This analysis has been made on 7×7 pixels squares, the so-called "super-pixel", which correspond more or less to the average PSF dimension. It has been found that $\sigma_{\rm pixel} \sim 1.7\ \sigma_\gamma$, where σ_γ denotes the photon noise. The value of $\sigma_{\rm pixel}$ and $(\Delta F_{\rm pixel})_{\max}$ at the maximum as well as their ratio are listed in Table 1. The ratio $\sigma_{\rm pixel}/(\Delta F_{\rm pixel})_{\max}$ has mean value 0.078 ± 0.026. Therefore, for $Q = 2$, we obtain $\delta_{\rm th} \simeq 15\%$ for the detection of anomalies near the maximum.

For 'optimal image subtraction', the effective rms fluctuation can be pushed closer to the photon-noise limit (Alard & Lupton 1998), yielding $\sigma_{\rm pixel} \sim 1.2\ \sigma_\gamma$, so that the detection threshold reduces to $\delta_{\rm th} \simeq 10\%$.

4. Detection probability for planetary signals

For μL events towards M31, the lens can be located in the Milky Way halo, the M31 halo, or the M31 bulge. It is almost impossible to discriminate among these different possible locations of the lens from a single observed light curve, though for a very small subset of microlensing events it is possible to tell something about the lens location (Han & Gould 1996). Since we expect only those events for which the lens is in the M31 bulge as being due to stars, we will consider only those events as potential targets for a search for planetary anomalies.

Table 1. The rms fluctuation $\sigma_{\rm pixel}$ and the maximum flux variation $(\Delta F_{\rm pixel})_{\max}$ for the 19 AGAPE candidate events towards M31, analyzed using the super-pixel photometry method (Ansari et al. 1997).

#	$\sigma_{\rm pixel}$	$(\Delta F_{\rm pixel})_{\max}$	$\sigma_{\rm pixel}/(\Delta F_{\rm pixel})_{\max}$
1	90	850	0.106
2	82	680	0.121
3	78	1286	0.061
4	99	870	0.114
5	85	900	0.094
6	44	870	0.050
7	46	1200	0.038
8	37	1110	0.033
9	53.5	830	0.064
10	73	940	0.077
11	100	620	0.094
12	56	645	0.121
13	101	945	0.107
14	63	1320	0.048
15	48	790	0.061
16	53	600	0.089
17	55	780	0.071
18	60	807	0.074
19	54	860	0.063

As pointed out before, one also needs a small impact parameter in order to produce an observable signal. Therefore, we restrict our attention to events that satisfy the following two conditions

1. $u_0 < u_{\rm th} \equiv 0.1$;[3]
2. lens in the bulge or in the disk of the target galaxy.

Since we need more than one observed data point to be confident that we observe a μL anomaly, we require an observable anomaly to deviate by more than $\delta_{\rm th}$ *and* during more than $t_{\rm E}/100$, i.e. ~ 7 hours for a month-long event, therefore requiring some dense sampling over the peak of the μL event. The probability to detect a signal depends on the projected separation d between the star and the jupiter-like planet, as defined in Sect. 2. Our calculation of the detection probability is similar to the one done by Griest & Safizadeh (1998), but we use different detection criteria here. For calculating the magnifications, we have used the approach developped by Dominik (1995), released as 'Lens Computing Package (LCP)'.

The "cross section" of the central caustic depends strongly on the direction of the source. Due to the elongated shape along the lens axis, it has a maximum for trajectories orthogonal to this axis, and a minimum for parallel trajectories. We have calculated the largest impact parameter $u_{\max} \leq u_{\rm th}$ that satisfies

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[3] For smaller $u_{\rm th}$, the detection probability will be larger.

our detection criterium for several different source directions. The detection probability for a planet for each of the considered directions α is then simply given by $P(\alpha) = u_{\max}(\alpha)/u_{\rm th}$, using the fact that the distribution of impact parameters is approximately uniform for small impact parameters for events from microlensing experiments towards unresolved star fields. The final detection probability has been calculated by averaging over the different trajectories. The results are shown in Fig. 1.

For both values of $\delta_{\rm th}$, there is some reasonable probability to detect planetary signals for planets in the lensing zone (i.e. the range of planetary position for which the planetary caustics is within the Einstein ring of the major component of the system, $0.618 \leq d \leq 1.618$. In agreement with previous work (Griest & Safizadeh 1998; Dominik 1999), the detection probability reaches a maximum for planets located close to the Einstein ring of their parent star (the caustic size increases towards $d \simeq 1$). Averaged over the lensing zone, the detection probability is $\sim 20\%$ for $\delta_{\rm th} = 15\%$ and $\sim 35\%$ for $\delta_{\rm th} = 10\%$.

With a 2m-telescope, one can detected ~ 400 events per year towards the M31 bulge (Han 1996). Present-day microlensing surveys towards M31 are still far away from such a theoretical limit, but the technique has demonstrated to be successful, and fruitful developments can be expected in the near future. With $\sim 50\%$ of these events being due to M31 bulge lenses (Han 1996) and $\sim 50\%$ of these bulge lens events having $u_0 < 0.1$ (Baillon et al. 1993), one can expect to detect up to 35 anomalies caused by Jupiter-like planets per year if every M31 bulge star has such a planet in its lensing zone.

To be able to observe and characterize the planetary anomaly, frequent observations (every few hours) during the anomaly are necessary. Future observing programs towards M31 or other neigboring galaxies should take this into account.

5. Extraction of planetary parameters

There is a crucial difference between the detection of a signal that is consistent with a planet and the detection of a planet, i.e. the determination of parameters that unambiguously characterize its nature. In fact, it has been shown that the first microlensing event MACHO LMC-1 is consistent with a planet (Rhie & Bennett 1996; Alcock et al. 2000). However, it appears to be consistent with a binary lens of practically any mass ratio q (Dominik & Hirshfeld 1996), so that the existence of a planet cannot be claimed from this event.

However, most of the papers about the detection of planets only show the possibility that a signal which arises from a planet can be detected (Mao & Paczyński 1991; Griest & Safizadeh 1998; Safizadeh et al. 1999), while the question about the extraction of parameters has only been addressed by a few people. Dominik (1997) has stressed that this is complicated by several points: there may be several different models that are consistent with the data, the fit parameters have finite uncertainties (in particular blending strongly influences $t_{\rm E}$), and the physical lens parameters only result on a stochastical basis using assumptions about galaxy dynamics. Gaudi & Gould (1997) have shown that one needs frequent and precise observations to determine the mass ratio q and the separation d from type II anomalies.

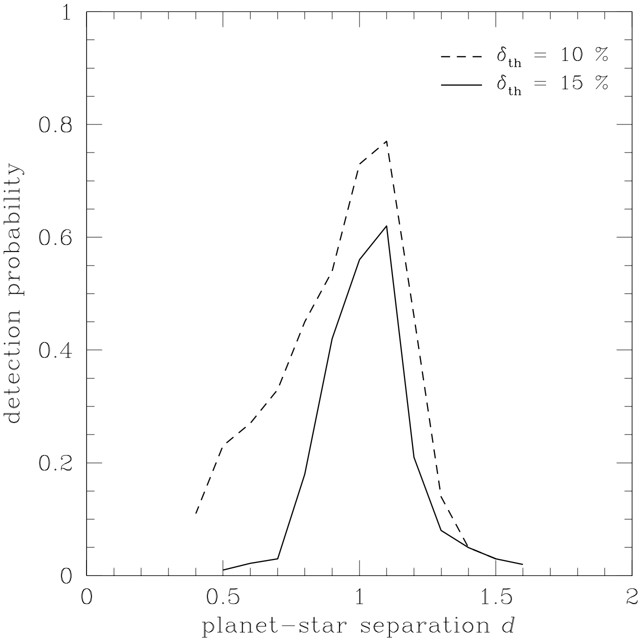

Fig. 1. The probability to see a deviation larger than $\delta_{\rm th} = 10\%$ or $\delta_{\rm th} = 15\%$ caused by a Jupiter-like planet ($q = 10^{-3}$) that lasts more than $t_{\rm E}/100 \sim 7$ hours as a function of the projected separation d between star and planet in units of Einstein radii

However, it is more difficult to constrain these parameters in type I anomalies. Additional complication arise because one does not obtain information about the time separation between the main peak and the planetary peak, there is a degeneracy between d and q (Dominik 1999), and observed anomaly results from the combined action of all planets around the lens star (Gaudi et al. 1998). Despite of the question whether d and q are well-determined, those parameters do not give the mass of the planet m, nor its true separation a. Moreover, an additional uncertainty enters because $d = a_{\rm p}/r_{\rm E}$ corresponds only to the projected instantaneous separation $a_{\rm p}$. Using models for the galactic dynamics, rather broad probability distributions for a and m result. Finally, we would like to point out the difficulties of distinguishing a genuine μL event from a variable star, which is particularly present in M31 μL experiments, due to the difficulties of measuring the effective baseline flux of the lensed star, and even more in case of anomalous events: great attention has to be paid to the cut-off to apply to variable stars.

However, as we stated before, photometric microlensing is the only method able to detect signals of planets around stars in M31, so that if there is a way to find planets, this is the only one. Although it is clear that a careful estimate of the fraction of events with planetary anomalies has to be performed, taking into account more details of the background noise, the binary sources events, the intrinsic variability phenomena, and all the other possible sources of error, and then checking whether the planetary signal comes out significantly, as we have shown with a first estimate, the prospects for detecting planetary signals are good. This means that even if planets can be truly characterized in only a fraction of the events where signals consistent with a planet can be detected, there is still a chance for being able to claim a planet. Such a subset of events could e.g. consist of events where the source trajectory crosses the caustic. Such caustic crossing events are likely to provide additional information.

A complete discussion of the extraction of planetary parameters is beyond the scope of this paper and will be presented elsewhere (Dominik & Covone, in preparation).

6. Summary and conclusions

While microlensing is already the only method to detect planets around stars that are at several kpc distance, namely by precise and frequent monitoring of μL events towards the Galactic bulge, future μL experiments towards nearby galaxies as M31 can even push this distance limit much further.

Pixel lensing and difference image photometry have demonstrated to be successful methods to search for μL events towards unresolved star fields, and improvements are expected from the 'Optimal Image Subtraction (OIS)' technique (Alard & Lupton 1998).

While AGAPE recently reported the observation of the possible first anomalous μL event towards M31 (Ansari et al. 1999), we have shown that even planetary systems can give rise to measurable anomalies. These planetary anomalies are due to passages of the source close to the central caustic near the parent star, i.e. the detection channel discussed by Griest & Safizadeh (1998).

Using the estimate of Han (1996) that about 400 events per year towards M31 can be detected with a 2m-telescope, we estimate that up to 35 jupiter-mass planets per year can be detected if they exist frequently in the lensing zone around their parent star. Further work has to be done in order to take into account the above mentioned difficulties. Following theoretical work by Gaudi & Sackett (2000), PLANet (Albrow et al. 2000) and MPS and MOA (Rhie et al. 2000) have recently published first results concerning the determination of the abundance of planets from the absence of observed signals. From our estimates it follows that future μL experiments towards M31 can have the power to yield strong constraints on the abundance of jupiter-mass planets.

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