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Detection of brown dwarfs by the micro-lensing of unresolved stars

P. Baillon[1], A. Bouquet[2], Y. Giraud-Héraud[3], and J. Kaplan[2]

[1] CERN, CH-1211 Genève 23, Switzerland
[2] Laboratoire de Physique Théorique et Hautes Energies, Universités Paris 6 and Paris 7, Unité associée au CNRS (UA 280), 2 Place Jussieu, F-75251 Paris Cedex 05, France
[3] Laboratoire de Physique Corpusculaire, Collège de France, Laboratoire associé au CNRS-IN2P3 (LA 41), F-75231 Paris Cedex 05, France

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Abstract. The presence of brown dwarfs in the dark galactic halo could be detected through their gravitational lensing effect and experiments under way monitor about one million stars to observe a few lensing events per year. We show that if the photon flux from a galaxy is measured with a good precision, it is not necessary to resolve the stars and besides more events could be observed.

Key words: Galaxy: halo – cosmology: dark matter – cosmology: gravitational lensing

1. A modest proposal

Many observations suggest that galaxies are embedded in massive spheroidal dark halos (Faber & Gallagher 1979; Kormandy & Knapp 1987; Trimble 1987; Turner 1990) which could be made of compact baryonic objects such as jupiters or brown dwarfs (Carr & Bond 1984; Rees 1986). Paczynski showed that such dark objects could be detected through gravitational lensing: the light of a star is amplified when a brown dwarf gets in the line of sight (Paczyński 1986). As the brown dwarf moves relative to the line of sight, this amplification varies in a characteristic way with time. The main problem is the low probability of such a micro-lensing event: about 10^6 stars must be monitored for one year to observe one 30% luminosity increase. Nevertheless, several experiments are under way (Alcock et al. 1989; Moniez 1990; Ansari 1992).

We suggest that, instead of monitoring individual stars, one could detect the flux amplification due to the lensing of one *unresolved* star in a dense star field, if the global luminosity of the field can be measured with sufficient accuracy. Then *every* star in the field is a candidate for a micro-lensing, not only the few resolved stars, and therefore the event rate is potentially much larger. Of course, not all micro-lensing events can be detected. Since the photon flux coming from a star is a small fraction of the flux coming from the field, only the lensing of bright stars can be detected (but they are rare), unless the amplification is very strong (but this is a rare event also because it requires a close alignment of the brown dwarf with the star). There are two promising targets, the central bar of the Large Magellanic Cloud (LMC) and the Andromeda galaxy M 31. Our proposal can be implemented with photon counters or with CCD cameras (better angular resolution but less precision on the flux). We report here the result of both studies which conclude to a higher efficiency than the standard procedure. Details of the method and full computations will be described in forthcoming papers. We first estimate the photon flux received on a pixel, the required amplification needed to detect an increase and the corresponding event rates (after recalling a few basic formulas for micro-lensing).

2. Fluxes and amplification

To evaluate the required amplification, we need to know the number of photons received on one pixel of the detector during an exposure, from the lensed star and from the host galaxy. It is easy to evaluate the photon flux F_{star} received from a star of given magnitude, if we approximate it by a black body, at a temperature given by its color index $B-V$. The flux received on the pixel from the galaxy is just the sum $F_{\text{gal}}=\sum_{\text{stars}} F_{\text{star}}$ of the fluxes from the stars which lie in the field of view of the pixel. This sum is given by the integral over the luminosity function of the target galaxy, i.e. the density of stars as a function of their magnitude and spectral class. This function is not well known: it is measured in limited areas, for bright stars only, and the only spectral information we have is a separation between main sequence stars and red giants (Hardy et al. 1984; Ardeberg et al. 1985; Hodge et al. 1988). For lack of a better information, we use the quoted data, assuming all red giants to be in the K class, and we completed them at the faint end by the luminosity function

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of the solar neighborhood (Allen 1973), with an empirical relative normalisation. The resulting luminosity function is then normalised to the measured surface brightness of the galaxy in the area covered by the pixel (de Vaucouleurs & Freeman 1972; Kent 1983; Walterbos & Kennicutt 1987). We checked that the expected rate of micro-lensing events is not very sensitive to the chosen luminosity function (Fig. 4). The total flux received on the pixel is the sum of this flux $F_{\rm gal}$ and of the flux $F_{\rm back}$ from the night sky background (Allen 1973). We take into account the absorption, and the quantum efficiency of the detector, which reduce the fluxes to a fraction of the photons arriving on top of the atmosphere. The total number of photons recorded during an exposure time $t_{\rm exp}$ on a pixel with a collecting area S is $N_{\rm tot}=(F_{\rm gal}+F_{\rm back})St_{\rm exp}$.

This number actually is a random variable, with mean value $N_{\rm tot}$ and standard deviation σ:

$$\sigma=\sqrt{N_{\rm tot}}=\left[\left(\sum_{\rm stars}F_{\rm star}+F_{\rm back}\right)St_{\rm exp}\right]^{1/2}. \quad (1)$$

Statistical fluctuations therefore limit the relative accuracy of the photometry to be worse than $\sigma/N_{\rm tot}=1/\sigma$. To get a feeling of the numbers involved, we consider two reference detectors, a CCD camera and a photomultiplier array, the characteristics of which are given in Table 1 below. The statistical accuracy is about 2% for the CCD camera pointing to an area of $\mu=21$ mag arcsec^{-2} for an exposure time $t_{\rm exp}=1/4$ h, and about 10^{-4} for the photomultiplier array in the same conditions. Longer exposure times, or larger collecting areas, improve the situation. However, there are unavoidable sources of spurious fluctuations, such as a luminous object passing through the field of view, a change in the background light or in the transparence of the atmosphere... Such effects limit in practice the photometric accuracy, and will probably require two identical telescopes operating in coincidence (as in one proposed Thémistocle upgrade). Another source of unwanted fluctuations comes from the limited pointing accuracy of the telescope: the number of stars on a pixel is also a random variable, and it fluctuates from one pixel to another. An imperfect pointing of the telescope then makes the matching of pixels from one image to the next more difficult, and this induces spurious luminosity fluctuations. Work is now in progress to assess and overcome the effects of these pointing uncertainties, but they are neglected in this paper.

To claim a positive observation of a micro-lensing, we require a minimal amplification $A_{\rm min}$ such that the increase $(A_{\rm min}-1)\,F_{\rm star}\,S\,t_{\rm exp}$ in the number of photons is Q times ($Q=3, 5, 10, \ldots$) the standard deviation $\sigma=\sqrt{N_{\rm tot}}$. Then:

$$A_{\rm min}=1+Q\frac{\sqrt{(F_{\rm gal}+F_{\rm back})\;S\,t_{\rm exp}}}{F_{\rm star}\,S\,t_{\rm exp}}. \quad (2)$$

When the pixel aperture is very small, around 1 arcsec^2 as on CCD cameras, Eq. 2 must be corrected. The mean number of stars on a pixel is small, and one star may dominate the luminosity of the pixel. When a bright star sits on a pixel, the flux $F_{\rm star}$ received from this star alone can be larger than the mean flux $\langle F_{\rm gal}\rangle$ received on neighboring pixels, and we use the formula $F_{\rm gal}\simeq F_{\rm star}+\langle F_{\rm gal}\rangle$. Seeing is another complication for small apertures: only a fraction f of the flux of a star reaches the pixel, and we must replace $F_{\rm star}$ by $fF_{\rm star}$. The remaining light is spilled over neighboring pixels, but this is usually compensated by the spilled light from neighboring pixels, unless the light distribution of the target galaxy is very irregular. Hence, Eq. 2 is modified as:

$$A_{\rm min}=1+Q\frac{\sqrt{(fF_{\rm star}+\langle F_{\rm gal}\rangle+F_{\rm back})\;S\,t_{\rm exp}}}{fF_{\rm star}St_{\rm exp}}. \quad (3)$$

Seeing effects spread the light of a star over several pixels and increase the amplification needed to detect a micro-lensing. On the other hand, this spread also reduces the spurious fluctuations due to bad pixel matching.

Contrary to our naive intuition, it turns out that amplifications are not very large for detectable lensing events. Figure 1 shows that amplifications are seldom much greater than 10, for both target galaxies. We did find some large amplifications ($A_{\rm min}>100$) in our Monte-Carlo simulations, but they are very rare. It appears to be more efficient to weakly amplify a few bright stars than to strongly amplify many faint stars, and this can be traced back to the slope of the luminosity functions (Allen 1973; Hardy et al. 1984; Hodge et al. 1988). Indeed, the lensed stars (for detectable events) are mostly main sequence stars in the LMC, and red giants in M 31 (see Fig. 2).

3. Basics of micro-lensing

When a massive object comes at a distance R to the line of sight of a star, the star light is amplified by a factor $A(R)$:

$$A(R)=\frac{R^2+2R_{\rm E}^2}{R\sqrt{R^2+4R_{\rm E}^2}}, \quad (4)$$

where the Einstein radius $R_{\rm E}$ is defined by:

$$R_{\rm E}^2=\frac{4GM_{\rm bd}}{c^2}\frac{D(D_{\rm star}-D)}{D_{\rm star}} \quad (5)$$

for a deflector of mass $M_{\rm bd}$ at a distance D, and a star at distance $D_{\rm star}$ from the observer (Paczyński 1986). Note that, for $R\ll R_{\rm E}$ the amplification $A\simeq R_{\rm E}/R$. Brown dwarf masses range (De Rújula et al. 1992) from $10^{-7}M_\odot$ (evaporation limit) up to $10^{-1}M_\odot$ (hydrogen burning limit). The Einstein radius sets the scale of the lensing: for instance, the amplification stays larger than A for a time $t_{\rm event}\simeq R_{\rm E}/AV_\perp$ if the brown dwarf has a transverse velocity $V_\perp$. Numerically:

$$t_{\rm event}\simeq 10^5\,{\rm s}\,\frac{1}{A}\,\frac{200\,{\rm km\,s^{-1}}}{V_\perp}$$

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Table 1. Main parameters of the detectors

Detector	Photon counter	CCD camera
Collecting area (m^2)	1	0.125
Field of view	Elliptical $60' \times 14'$	Rectangular $64' \times 22'$
Number of pixels	1000	3.7×10^6
Aperture per pixel ($arcsec^2$)	2300	1.36

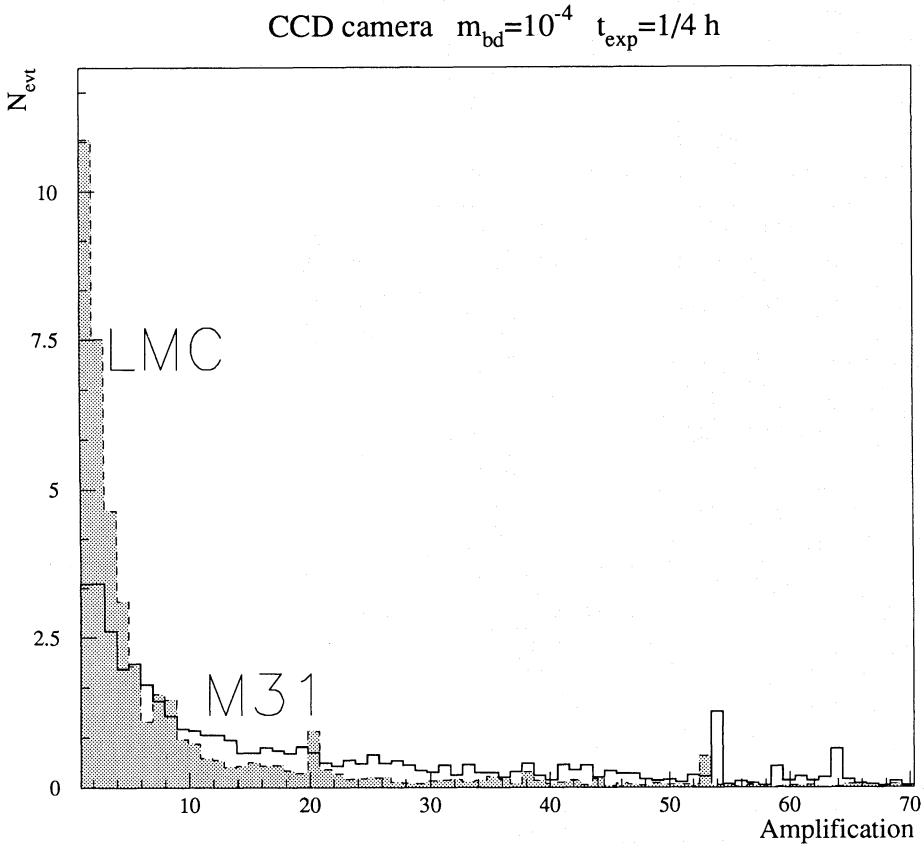

Fig. 1. Amplification distribution for the CCD camera pointing at the LMC or M 31, for a brown dwarf mass $M_{bd}=10^{-4}M_{\odot}$ and an exposure time t_{exp} = 1/4 h

$$\left(\frac{M_{bd}}{10^{-4}M_{\odot}}\frac{D}{25\,\mathrm{kpc}}\frac{D_{star}-D}{D_{star}}\right)^{1/2}. \quad (6)$$

The event rate Γ_{star} (number of micro-lensing events that can be detected per unit time) for a given star is simply the number of brown dwarfs which come close enough to the line of sight to yield a mean amplification, during the exposure time, above some threshold A_{min}. This number depends on the required amplification A_{min}, on the brown dwarf number density in the direction of the star, and on the brown dwarf mean transverse velocity $V_{\perp}$. The total number of micro-lensing events detected during the observation time t_{obs} then is the sum over all stars of the number of events for each star:

$$N_{events}=t_{obs}\sum_{star}\Gamma_{star}. \quad (7)$$

We assume that our Galaxy is embedded in a massive dark halo made of brown dwarfs, described by an approximate isothermal distribution with a core radius a. We took all brown dwarfs to be of equal mass M_{bd}. Of course, we do not expect this to be true, but 1) the actual mass distribution is totally unknown, and 2) this allows to probe the sensitivity of different experimental conditions for various brown dwarf masses. The brown dwarf number density $n(r)$ is:

$$n(r)=\frac{\rho_{\odot}}{M_{bd}}\frac{r_{\odot}^2+a^2}{r^2+a^2}. \quad (8)$$

It is cut-off at a maximal radius r_{max} which is unknown, and we shall assume that it extends up to 100 kpc in numerical estimations. The halo mass density $\rho_{\odot}$ in the solar neighborhood is estimated to be $0.008\,M_{\odot}\,pc^{-3}$

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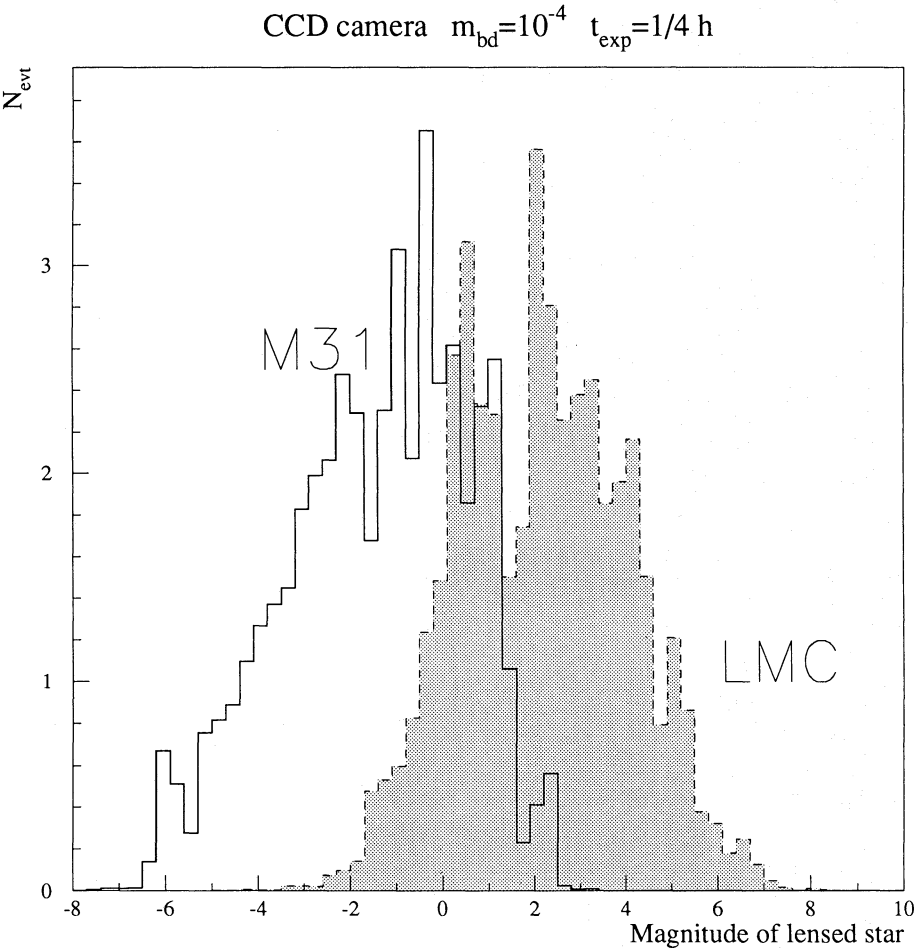

Fig. 2. Magnitude distribution of the lensed stars for the CCD camera pointing at the LMC or M 31, for a brown dwarf mass $M_{bd}=10^{-4}M_{\odot}$ and an exposure time t_{exp} = 1/4 h

(Flores 1988). The distance $r_{\odot}$ between the Sun and the galactic center is 8.5 kpc, and estimates of the core radius range from $a=2$ kpc (Bahcall & Soneira 1980) to $a=8$ kpc (Caldwell & Ostriker 1981), and we shall take $a=5$ kpc for definiteness. We also assume that brown dwarfs have a Maxwellian velocity distribution, with a uniform velocity dispersion of 270 km s^{-1}.

Equation 4 is only valid for point sources, and should be modified for extended sources such as stars. Actually, the shape of $A(R)$ is not very different from the point-like case, except that there is an upper limit A_{max} on the amplification of an extended source by micro-lensing. This limit is reached in the case of perfect alignment (where the amplification of a point-like star would be infinite). A surface element of the star at a distance y from the center is then amplified by a factor $A(y)$:

$$A(y)=\frac{(yD/D_{star})^2+2R_E^2}{yD/D_{star}\sqrt{(yD/D_{star})^2+4R_E^2}} \tag{9}$$

and

$$A_{max}=\frac{1}{\pi R_{star}^2}\int_0^{R_{star}} A(y)2\pi y\,dy=\left[1+\left(2\frac{R_E(D)/D}{R_{star}/D_{star}}\right)^2\right]^{1/2}. \tag{10}$$

For a given star and a given brown dwarf mass, this leads to an upper bound D_{max} on the distance D of a brown dwarf, which becomes small for large amplifications or large stellar radii [the radius of a given star is related to its spectral class and magnitude (Allen 1973)]. This effect reduces the number of detectable lensings of red giants, or the lensing efficiency of lighter brown dwarfs. For instance, Fig. 3b shows that light brown dwarfs of the halo of M 31 do not lead to detectable lensings.

4. Number of events

We use two methods to compute the expected number of micro-lensing events: a Monte-Carlo simulation, and a semi-analytic method. The results obtained are very similar, and allow a cross-check of the accuracy of both computations.

Our Monte-Carlo procedure is the following. We choose a brown dwarf of fixed mass with random position in the galactic halo (and also in the halo of M 31 when this galaxy is the target) according to the brown dwarf density distribution $n(r)$, and with random velocity according to a Maxwellian distribution. Around the line of sight between the Earth and this brown dwarf we define a "useful

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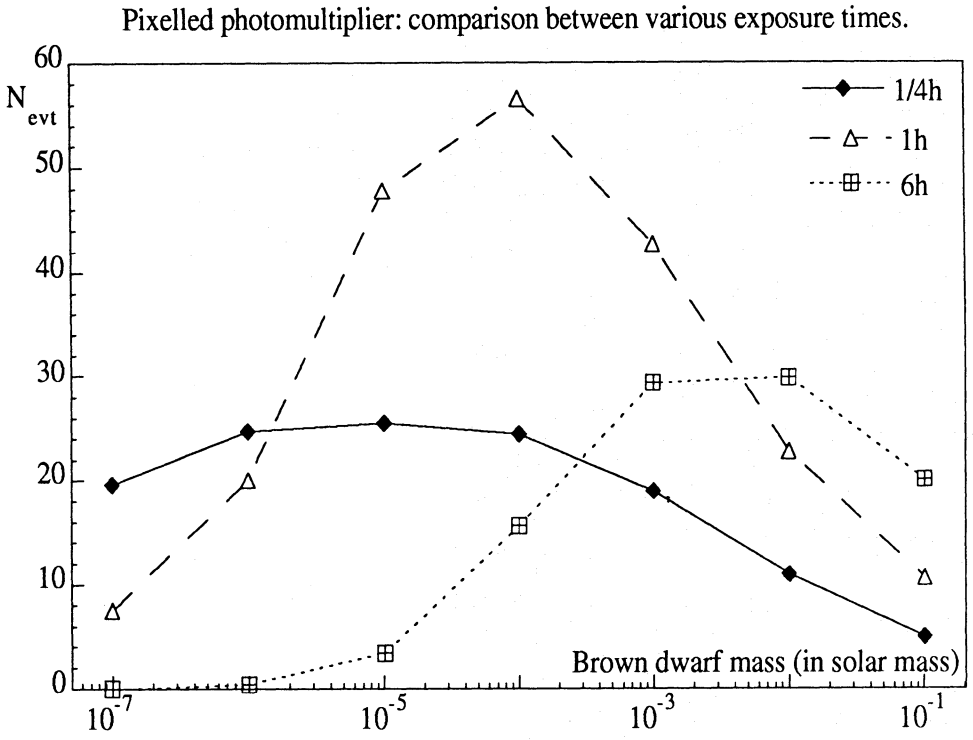

Fig. 3a. Number of detected micro-lensing events per year for the photomultiplier array pointing to M 31, as a function of the brown dwarf mass. The curves correspond to 3 different exposure times, $t_{exp} = 1/4$, 1 and 6 h

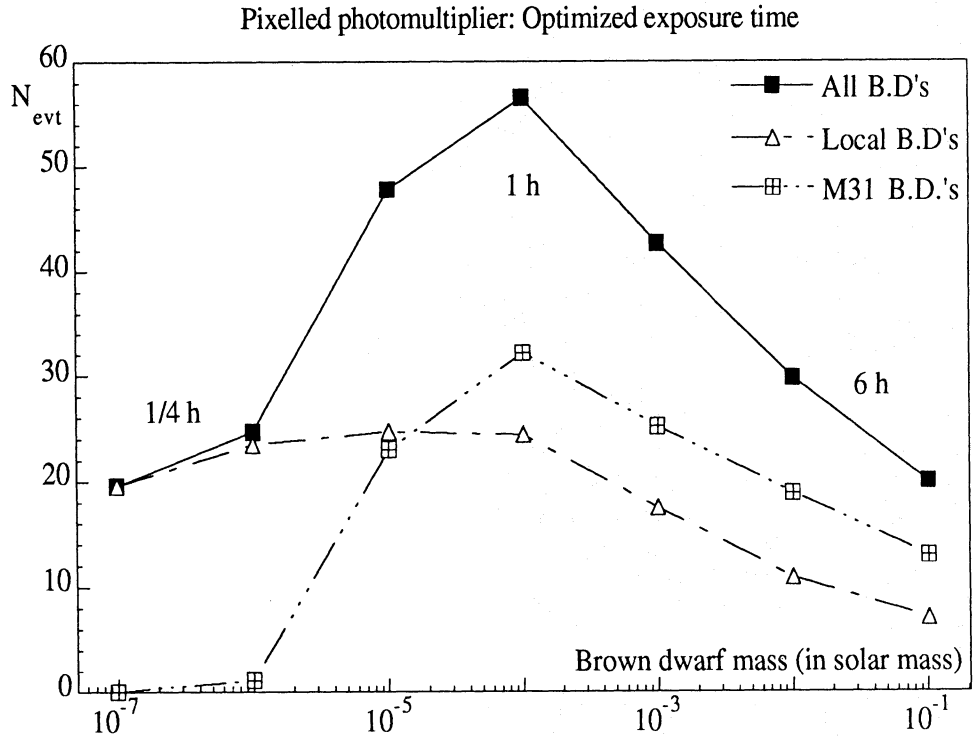

Fig. 3b. Number of detected micro-lensing events per year for the photomultiplier array pointing to M 31, as a function of the brown dwarf mass. The exposure time was optimized according to the brown dwarf mass. The curves show the number of events due to brown dwarfs of our halo, of the halo of M 31, and the total number of events

angular area" characterized by the Einstein angle $R_E(D)/D$ and the extrapolated angular trajectory of the brown dwarf during the year. We then pick up a uniformly distributed star in the projection of this area on the plane of the target galaxy. In order to keep the computation time reasonable, we affect to each event a weight reflecting the density, magnitude and spectral distribution of stars. This weight is eventually normalised to the local surface brightness. In a second step, we follow the trajectory of the brown dwarf for one year and check whether it gets close enough to a star to lead to a detectable amplification of the starlight. When large amplifications are required, micro-

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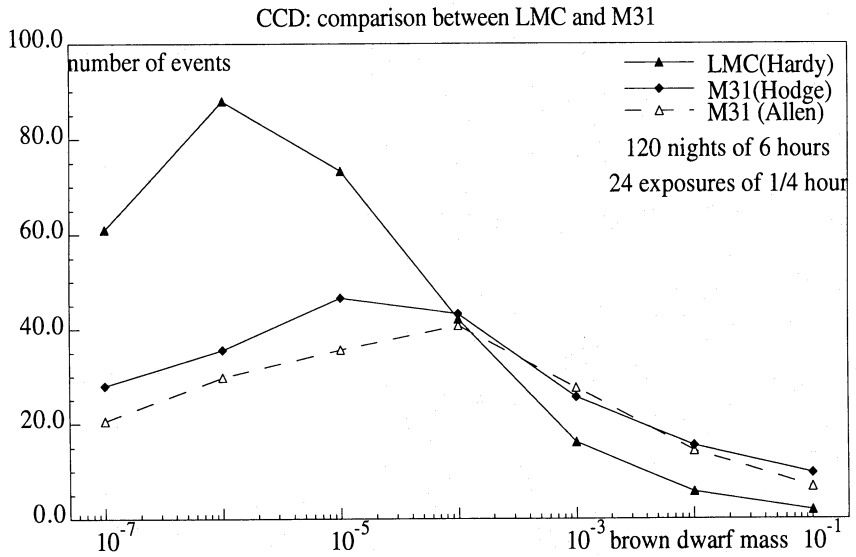

Fig. 4. Number of detected micro-lensing events per year for the CCD camera pointing to the LMC and to M 31, as a function of the brown dwarf mass. The solid curves are obtained with the true luminosity function of the LMC (Hardy et al. 1984) and of M 31 (Hodge et al. 1988). The dashed curve uses the solar neighborhood data over the whole range of magnitudes

lensing events are short, their duration becomes comparable to the exposure time t_{exp} and the amplification changes during the exposure. We thus compute the mean amplification $\bar{A}$ during the exposure and require $\bar{A} > A_{min}$. We store the corresponding event for further analysis, and repeat the whole procedure, a few million times for each value of the unknown parameters (the mass distribution of brown dwarfs, the exposure time, the detector characteristics, etc.).

In the semi-analytic method, we again compute for a given star the mean amplification $\bar{A}$ during the exposure and require $\bar{A} > A_{min}$. For each star, this defines a volume Δ around the line of sight, in which a brown dwarf must lie at time $t=0$ (the middle of the exposure) to yield an observable effect. The number of micro-lensing events which can be seen during a given exposure is nothing but the number of brown dwarfs which lie in the volume Δ of each star, summed over all stars in the field of view of the pixel. This number of brown dwarfs is just the integral over Δ of the number density n, and the sum over stars is the integral over the luminosity function (normalised to the surface brightness of the galaxy). The amplification can remain above threshold for several exposures, and to avoid multiple counting, one must only count for each exposure brown dwarfs which were not yet inside the volume during the preceding exposure. These brown dwarfs, efficient for the first time, lie in a smaller volume Δ', obtained by substracting from volume Δ the volume Δ shifted by $V_\perp(t_{inter}+t_{exp})$ where t_{inter} is the time interval between the two exposures, and $V_\perp$ the transverse velocity of the brown dwarf. The total number of micro-lensing events during the whole observation is the number of new events per exposure, times the number of exposures N_{exp} done during the total observation time t_{obs}, i.e.:

$$N_{events} = N_{exp} \sum_{stars} \int_{\Delta'} n(r, V_\perp)\, d^3r d^2V_\perp . \quad (11)$$

We recover the usual formula (Griest 1991) when the exposure time t_{exp} is much shorter than the event duration. The section of volume Δ' then is a narrow crescent, of radius $R_E(D)/A_{min}$ and width $V_\perp(t_{inter}+t_{exp})$, and:

$$N_{events} = (t_{inter}+t_{exp}) \; N_{exp} \sum_{stars} \left\{ \int_0^{D_{star}} \frac{2R_E(D)}{A_{min}} V_\perp n(D, V_\perp)\, dD d^2V_\perp \right\}. \quad (12)$$

The product $(t_{inter}+t_{exp})N_{exp}$ is the total observation time t_{obs}, and the expression between braces is nothing but the event rate Γ_{star}, which becomes independent of the star when the threshold amplification A_{min} is constant and all stars are nearly at the same distance.

5. Proposed experiments

Our initial idea to use the present setting of the Thémistocle experiment (Kovacs 1990; Baillon 1992), in the south of France, proved unrealistic. With only one photomultiplier counting photons from the *whole* Andromeda galaxy M 31, such an experiment could detect a few events per year, but required a 10^{-8} photometric accuracy (and extreme stability). The field of view of a detector must be small to detect with an achievable photometric accuracy the lensing of one star. But the number of stars in the field of view will then be small, and therefore the number of lensing events will also be small. The solution is to add many detectors, or rather to pixellize the detector. We studied two cases: 10^3 pxl and 10^6 pxl. The first solution can be achieved with an array of Hybrid PhotoDiode (HPD) tubes, and the second one with a typical CCD camera.

HPD tubes are equipped with a silicon wafer anode which converts accelerated photoelectrons (20 keV or more) into 10^4 to 10^5 electron-hole pairs. Such HPD tubes

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are under development for LHC experiments (DeSalvo et al. 1991). Their main advantage is that they count incoming photoelectrons one by one without loss and noise. Therefore, the light flux that reaches a definite pixel is measured with a very high accuracy. Another advantage is that they continuously record photons as they arrive on the detector. Therefore, it is possible to look back at the record, and add the number of photons received in bins of variable duration to fit best the actual duration of a lensing event, which can range between a few minutes and a few weeks, and to reconstruct the typical shape of the micro-lensing light curve. Figure 3a shows how this optimization of the exposure time improves the sensitivity of the experiment. The main drawback of photomultipliers is that the number of pixels cannot be very large, a few thousands at most. A lensing event then has to emerge above a large background, and it requires a very good photometric accuracy to be detected, at least of the order of 10^{-4}. On the other hand, the relatively large angular size of large pixels (of the order of one arcmin) does not require a mirror of extremely good optical quality. To be precise, we do our estimates for a set-up corresponding to a reduced version of a planned Thémistocle upgrade, namely a mirror with a collecting area of 1 m^2, and 1000 pxl. This can be realized with 50 HPD tubes with 20 pxl each, fed by optical fibers from the focal plane of a mirror. We assumed in our estimations that these 1000 pxl were set in a flattened elliptical pattern (with a semi-major axis of 30′, and a semi-minor axis of 7′), to follow the elongated shape of the two targets that we chose, the LMC and M 31. The full upgrade will have two telescopes, each with a 12.5 m^2 mirror and between 1000 and 2000 pxl at the focus.

CCD cameras have advantages and drawbacks opposite to photomultipliers. They have a very high spatial resolution and it is easy to have several millions pixels on a small surface at a reasonable cost. But their photometric accuracy is worse than photomultipliers, around 1% only. As a reference CCD camera, we took the characteristics of the ongoing "Naines Brunes" experiment (Moniez 1990; Ansari 1992): a camera with 2×8 CCD chips of 564×410 pxl each, at the focus of a 40 cm diameter mirror. The photon detection efficiency was taken in both cases to be 20% in the V (visible) band, taking into account the quantum efficiency of the detector, the absorption through the atmosphere, and the mirror reflexion losses (Allen 1973). Parameters for the 2 detectors are summarized in Table 1.

We consider two possible targets: the Large Magellanic Cloud (LMC) and the Andromeda galaxy M 31. Each one has advantages, and drawbacks:

(i) The LMC can only be seen from the southern hemisphere, whereas M 31 is best seen from the northern hemisphere.

(ii) M 31 is much further away than the LMC, about 14 times, and therefore a detector sees 14^2 times more stars for the same aperture. This has two consequences. First, to be detected in M 31, a lensing usually requires a larger amplification (see Fig. 1) of a brighter star (see Fig. 2). Such an event is then rarer, but this is almost exactly compensated by the larger number of target stars. This larger average number of stars in a pixel has a second consequence: statistical fluctuations in the number of stars in a pixel will be smaller, and therefore less precision is required in pointing the telescope, and in matching pixels from one image to another.

(iii) If the target galaxy also is embedded in a brown dwarf halo, then additional micro-lensings occur due to these brown dwarfs. The Magellanic Clouds are embedded in our galactic halo and (probably) have no halo of their own. On the contrary, the rotation curves of M 31 show that it is surrounded by a dark halo. Therefore brown dwarfs of this halo can act as gravitational lenses for stars in M 31, and we must add their contribution. To be conservative, we assumed the same halo for M 31 as for our galaxy, although the larger rotation velocities imply a larger dark matter density around M 31. We find that the contribution from the brown dwarfs of M 31 is slightly larger than the contribution from our own galaxy for heavier brown dwarfs (i.e. with masses in the range 10^{-3}–$10^{-1} M_\odot$) but negligible for lighter masses (see Fig. 3b).

6. Results

The foremost result is that the expected number of micro-lensing events is about one order of magnitude larger in both our proposals than in ongoing experiments (Alcock et al. 1989; Griest 1991; Ansari 1992), even though neither detectors were optimized for this brown dwarf search. We call an event "detected" if the luminosity of a definite pixel stays at 3 standard deviations above the background [that is $Q=3$ in Eq. (3)] for three consecutive exposures, and rises above 5 during one of them. In fact we often "found" events at $Q>10$.

Let us first focus on the photomultiplier array, pointing to M 31. Figure 3a shows the number of detected events as a function of the brown dwarf mass M_{bd}, for a duty cycle 120 nights of 6 h, and for three different exposure times. In such experiments the best sensitivity is obtained for brown dwarfs in the mass range 10^{-5}–$10^{-3} M_\odot$. The brown dwarf mass density being fixed, heavier brown dwarfs are less numerous and produce less lensing events. On the other hand, very light brown dwarfs, although more numerous, are not very efficient because their maximal amplification is low, and moreover they produce short lensing events, which can be too short to be detected. In this respect, short exposures (1/4 h) are adequate to detect light brown dwarfs (10^{-7}–$10^{-4} M_\odot$), whereas high mass brown dwarfs (10^{-3}–$10^{-1} M_\odot$) generate long lensing events and are best detected with exposures of the order of 6 h. These results show the interest of the photomultiplier device, which allows the tuning of the

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Table 2. Main results of simulations

Experiment	Naines Brunes	CCD→LMC	CCD→M 31	PM→LMC	PM→M 31
N_{events}	10	80	50	60	60
$\langle A_{min} \rangle$	1.34	9.6	23	7	14
$\langle Mag_V \rangle$	<0	2	-1	1	-2
Photometric accuracy	10^{-2}	10^{-2}	10^{-2}	10^{-4}	10^{-4}
Optimal M_{bd}	10^{-6}	$10^{-6}-10^{-5}$	10^{-4}	10^{-5}	10^{-4}
Lensed stars	Red giants	Main sequence	Red giants	Main sequence	Red giants

exposure time to the mass of the brown dwarf: incoming photons can be recorded one by one with a very short time binning, the time bins can then be lumped together at will.

Figure 3b shows the relative importance of brown dwarfs from our own halo and of brown dwarfs from the halo of M 31. As we said, both halos equally contributes above $M_{bd}=10^{-5}M_{\odot}$, but the importance of M 31 halo vanishes for lighter masses. This is due to the finite size effect: Equation (10) shows that for amplifications $A \gg 1$:

$$A_{max} \simeq 2 \frac{R_E(D)/D}{R_{star}/D_{star}} \quad (13)$$

that is, twice the ratio of the angular diameter of the Einstein ring to the angular diameter of the star. The Einstein radius R_E is about the same for brown dwarfs in our halo and in M 31 halo, but the *angular* diameter is much smaller for M 31 brown dwarfs, and the maximal amplification is therefore much smaller.

The exposure time cannot easily be varied for CCD's, and in any case cannot be changed after the exposure. CCD's must be read after a definite time, long enough to get a signal sufficiently above the reading noise, but short enough to avoid saturation. The exposure time was taken to be 1/4 h. Longer exposures can be achieved by combining successive images, but this is very expensive in computing time due to the large number of pixels, and the gain in statistical accuracy can be lost due to the difficulties in matching pixels between the combined images. For this reason, in the case of CCD cameras, we only show in Fig. 4 the expected counting rates for exposures of 1/4 h. As expected, the plot is strongly peaked towards low masses when looking at the LMC, just because the number density of brown dwarfs is larger for lighter masses. The decrease at the lower end of the mass range again reflects the shorter duration of lensing events. The decrease is stronger when the target is M 31, again because of the finite size effect: Fig. 2 tells us that target stars in M 31 are very luminous, and most of them are red giants with large diameters that limit the possible amplifications.

To check the sensitivity of our results to the luminosity function of the target galaxy, we compare in Fig. 4 the counting rates obtained taking for the bright stars of M 31 either the true data (Hodge et al. 1988) or the solar neighborhood data (Allen 1973). Clearly the change is not significant, and our poor knowledge of the luminosity function and spectral repartition does not affect the results.

How do our results compare with ongoing brown dwarf searches? Table 2 is a summary of our results: we compare our expected counting rates for different target galaxies (LMC vs. M 31) and different detectors (CCD camera vs. HPD tubes), to those announced by the "Naines Brunes" CCD experiment (Ansari 1992). However our evaluations do not take into account all experimental cuts.

What does Table 2 tells us? First, the expected number N_{events} of detected micro-lensings is larger when pixels are monitored instead of stars. The reason is that the "Naines Brunes" experiment only monitors stars of absolute magnitude less than 0 in the LMC, and is not sensitive to fainter stars. Figure 2 shows the distribution of the absolute magnitude of the lensed stars in the "detected" events in our CCD→LMC Monte-Carlo simulation. The shaded histogram corresponds to the LMC, and one can see that stars fainter than magnitude 0 represent nearly 90% of our detected events, hence the large increase in sensitivity from 10 events year^{-1} to about 80.

The expected number of events accidentally turns out to be similar when the target is M 31 or the LMC, or with a photomultiplier array instead of a CCD camera. Of course, events are different in each experiment.The requested amplifications A_{min} are of course larger than the value 1.34 of the "Naines Brunes" experiment. The requirement of higher amplifications for our proposals implies that they are automatically sensitive to higher brown dwarf masses than ongoing experiments. Amplifications are smaller for the photomultiplier experiment than for the CCD experiment, only because the photometric precision is much better and compensates the larger background due to the much larger number of stars on a pixel. The photometric accuracy $1/\sigma$ due to statistical fluctuations of the photon flux, computed from Eq. (1), is 10^{-2} for the CCD camera and 10^{-4} for the HPD array. It can be much smaller with a larger collecting area (for instance going from the 1 m^2 of our HPD example to the 25 m^2 of one Thémistocle upgrade), but other sources of noise may then dominate.

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7. Going further?

The estimates above were not performed for optimized experiments, but for existing (or planned) detectors built for other purposes. However, before a dedicated experiment can be undertaken, some proof of concept is obviously needed. Many weak points were left over in this work. One of the most blatant is the neglect of spurious fluctuations due to variables stars and pointing errors or bad pixel matching. Variable stars can in principle be distinguished from micro-lensing events, because in the latter case the light curve must have only one maximum, be time symmetric and achromatic. All these characteristics also hold in our case, but may be more difficult to check because we rely on a small flux increase over a large background. The achromaticity of the light *increase* could be checked by taking pictures in two colours, provided that the signal is strong enough in *both* colours. Pointing errors have less serious consequences for a distant target such as M 31 than for the LMC, because luminosity fluctuations are much smaller from one pixel to the next. The large pixels of photomultipliers also lead to smaller fluctuations, but as a higher photometric precision is needed, the situation is not better than for CCD cameras. These fluctuations can, to a large extent, be corrected if one requires that bright spots be at the same position on every picture.

All these problems are now under study, but a rudimentary test of our proposal could be done, for instance, using data already gathered by the "Naines Brunes" experiment (Ansari 1992). This experiment first produces a star catalog from a few CCD pictures, using pattern recognition. To decrease photometric errors and computer time, the remaining CCD pictures are then processed to extract the luminosity curves of the stars already in the catalog. A faint star absent from the catalog will not be monitored, but may appear on a few pictures when lensed by a brown dwarf. Such lensing events could be detected as transient stars, if the pattern recognition algorithm could be applied to all CCD pictures. A preliminary study indicates that the number of detected events could be doubled that way, but some work is needed to evaluate the background of fake events.

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