MICROLENSING OF UNRESOLVED STARS AS
A BROWN DWARF DETECTION METHOD

Alain Bouquet, Jean Kaplan, Anne-Laure Melchior
LPTHE, Universités Paris 6 et Paris 7, unité associée au CNRS UA280, 75251 Paris Cedex 05, France

Yannick Giraud-Héraud
Collège de France, laboratoire associé au CNRS/IN2P3 (LA 41), 75231 Paris Cedex 05, France

Paul Baillon
CERN, 1211 Geneva 23, Switzerland

Presented by Anne-Laure Melchior

ABSTRACT
We describe a project of brown dwarf detection in the dark halo of a galaxy using
the microlensing effect. We argue that monitoring pixels instead of stars could
provide an enhancement in the number of detectable events. We estimate the
detection efficiency with a Monte-Carlo simulation. We expect a ten-fold increase
with respect to current experiments. To assess the feasibility of this method we
have determined the photometric precision of a pixel by comparing several pictures
of a same field in the LMC.

1. Brown Dwarfs as Dark Matter

The dark halos of galaxies could be baryonic as suggested by the present nucleosyn-
thesis bounds. It may also explain the disc-halo conspiracy observed in the rotation
curves. Brown dwarfs, hypothetical compact hydrogen objects with a mass be-
tween the evaporation limit \(10^{-7} M_\odot\) and the nuclear burning limit \(10^{-1} M_\odot\), are a
favoured possibility.
Nearby brown dwarfs could in principle be directly detected by infrared observations\textsuperscript{5,6}. Several groups are looking for individual brown dwarfs within our galaxy. There are already candidates in the Pleiades\textsuperscript{7} which await to be confirmed. This procedure is not relevant for the dark matter in the halos, but it may prove that brown dwarfs exist. The halo of nearby galaxies might be detected by satellites through the integrated infrared emission\textsuperscript{6}. These observations should be mostly sensitive to heavier brown dwarfs.

Brown dwarfs could also be indirectly detected by the microlensing effect. A star or a brown dwarf passing near the line of sight of a source, deflects its light. Although the angular deviation is too small to be detected, the luminosity of the source is temporarily increased\textsuperscript{8,9,10,11}. This amplification provides a clear signature: the shape of the light curve should be achromatic, symmetric in time and not repeated. The microlensing phenomenon has been extensively presented in this conference\textsuperscript{12,13}.

Microlensings may have already been observed on quasars, sitting behind a galaxy\textsuperscript{14,15,16,17}. Flux variations attributed to microlensing of the quasar by individual starlike objects of the galaxy are expected to occur at a rather high rate: once about every few years. It is, however, difficult to distinguish between ordinary stars and brown dwarfs through this effect.

As suggested by Paczynski\textsuperscript{10}, microlensing events may be observed on stars of nearby galaxies. The rate of events per target is much lower (typically once every million years), but millions of stars can be followed. Experiments are now running, using stars in the Large Magellanic Cloud (LMC) as targets (MACHO\textsuperscript{18}/EROS\textsuperscript{19}). These experiments are sensitive to brown dwarfs over the whole mass range. Notice that this method is the only one to be sensitive to very low mass brown dwarfs.

This paper proposes an alternative method to detect microlensing events. Monitoring a galaxy by one million pixels instead of individual stars could significantly improve the detection efficiency.

2. Why Monitor Pixels rather than Stars?

The typical number of resolved stars is about $10^5$ for M31 and a few $10^6$ in the LMC, which may at most give rise to a few microlensing events per year. These galaxies, however, contain about $10^{10-11}$ stars so that the potential number of sources is quite large.

To take advantage of all these potential targets, we propose\textsuperscript{20} to monitor the light flux received by every pixel on the picture of a galaxy rather than the flux of the individual stars. In this way we will be able to detect the flux increase due the lensing of one of the (many) stars present on the pixel even if it is not resolved.

Still, all lensings will not be detectable: only those of the brightest stars or those which produce a high amplification. High amplifications mean a close approach of
the lens to the line of sight and therefore seldom occur.

With our proposed method, using the LMC as target we expect to gain a factor around 10 on the number of events, compared to ongoing experiments. This is illustrated on the following plot (figure 1) which displays the number of events we expect to detect with our method, as a function of the magnitude of the lensed stars. These numbers have been obtained, in the conditions of the EROS experiment, using a Monte Carlo simulation presented in more details below.

The limiting (visual) magnitude of the EROS experiment is around 19, and is indicated by a vertical line. The area under the curve, marked “stars”, corresponds to microlensings of monitored stars, whereas the area marked “pixels” corresponds to unresolved stars, the microlensings of which can only be detected through our method. We can see clearly the proportion of the resolved stars with respect with the unresolved ones, and the appreciable gain in the number of expected events.

Figure 1 : Magnitude of (unresolved) lensed stars

Another advantage of our method is that M31, where the number of resolved stars is limited, becomes a promising target21,20. The expected number of events is similar to the LMC target. Individual stars in M31 are fainter, so that higher and therefore rarer amplifications are needed for a star to stand out of the background, but this is compensated by the larger number of potential target stars in the field. Moreover, M31 possesses its own dark halo, the brown dwarfs of which also act as lenses.

3. How do we estimate the gain ?

We have estimated through a Monte-Carlo simulation the number of events we expect to be able to detect with a monitoring of the pixel luminosity. We present
here our study under the conditions of the EROS experiment \(^{19,13}\) in order to test the feasibility of our method.

We considered two galaxies of the Local Group: the L.M.C. (distance: 50kpc, angular extension: a few degrees, visible from the South hemisphere) and M31 the largest galaxy of the Local Group (700kpc, a few degrees, North Hemisphere). For both targets, we took the luminosity function of the stars from the literature when available, and used that of the solar neighbourhood otherwise (see Ref. for details).

Then, we selected at random a brown dwarf in the halo of the Milky Way and of the target galaxy, according to a simple halo model (density decreasing as \(1/(a^2 + r^2)\), Maxwellian velocity distribution, identical halo for M31 as for our galaxy, no halo for the LMC). We also selected at random a star in the target galaxy, with a weight proportional to the product of the surface luminosity of the target area with the star luminosity function. We then computed the amplification of the lensed star as a function of time.

If the amplification gets large enough, the light flux reaching the pixel in the direction of the star will temporarily rise above the fluctuations of the output of the pixel. If this rise is large enough, and lasts long enough we call this an event (see an example on figure 2).

Figure 2: Aspect of a detected microlensing event

The fluctuation of the pixel output can prevent the detection of an event. This fluctuation, defined as its standard deviation, includes several contributions:

i) The statistical fluctuation of the background light: the night sky luminosity plus the surface brightness of the target galaxy, corrected of course for the absorption by the atmosphere, the mirrors and filters and for the quantum efficiency of the CCD.

ii) The readout noise of the CCD.
iii) The residual errors due to imperfect matching of consecutive pictures.

We called an event a rise of the luminosity of a definite pixel above $3\sigma$ during 3 consecutive exposures reaching $5\sigma$ in at least one of them. We expect that fluctuations can only simulate such an “event” once every 50 years.

With the above requirements, for 120 nights 6 hours long, taking 15 minutes exposures, and a seeing around 2", we expect the number of events displayed in figure 3 as a function of the brown dwarf mass assumed here to be the same for all brown dwarfs of the halo. Of course we do not expect this to be true, but we know nothing about their mass distribution. This presentation then allows to assess the sensitivity to various brown dwarf masses.

Figure 3 : Expected number of microlensing events

The main limitations of this method come from the photometric precision one can achieve, and from the variable stars which will be the main background.

4. Photometric Precision

The number of detections expected depends crucially on the size of the fluctuations of the pixel output. Since it can never be smaller than the fluctuation of the number of photons reaching the pixel, the optimal situation is obtained when all other sources of fluctuations are of the same order of magnitude. In our simulation statistical fluctuations were of the order of a few percent, and we boldly assumed that all residual errors, the main source of which is the matching in position and intensity of successive pictures, could be kept at the same level. We have to check whether this is supported by real observations.
To this aim, the EROS collaboration provided us with a few pictures of the LMC in two bands (non-standard B and R filters). We studied 9 blue pictures of 100″ × 100″, with a seeing around 2″ and a pixel size of 1″. We find that the relative fluctuations are smaller than 4%. The mean value of the pixel for these pictures is about 1700 photons so that the corresponding statistical fluctuations are about 2.5 %, and therefore the residual errors are around 3%.

To check the efficiency of the picture-matching algorithm and to control the inputs of the Monte Carlo simulation, we elaborate some synthetic pictures adjustable to different targets (M31/LMC), luminosity function, experimental set-up, seeing, etc... We generate some random fields of stars and evaluate the fluctuations. This is a way to understand the different components of this fluctuation (statistics, pixel matching, noises, etc...). The results are compatible with the values measured on real pictures (see figure 4).

Figure 4 : Distribution of the relative rms of the pixel response estimated on 9 consecutive pictures (real and synthetic).

It is encouraging to note that, with observations not optimised for our experiment, we find a rather good photometric accuracy. So that the number of events we have evaluated seems valid. Of course, this evaluation must be confirmed with a larger sample of pictures.

5. Variable Stars

Variable stars constitute the main source of background events. As the selection criterium for the fluctuation requires an important signal, this method can also distinguish the events which are symmetric in time and unique. The achromaticity is more
difficult to check in our approach because the color of the lensed star may be different from the background color. Nonetheless, many events in our simulation stand out both in blue and in red, so one can study the time evolution of the event in both colors. In particular, the ratio between the light flux increases of the pixel in the blue and red bands should be constant in time.

Note that our method is sensitive to rather faint stars for a nearby target such as the LMC. Variable stars are mostly concentrated in a small region of the HR diagram: they are bright red stars. We expect a smaller relative number of variable stars in a larger magnitude sample and thus less background than the running experiments. This argument doesn’t hold for more distant galaxies like M31 where detectable events occur on brighter stars.

Nevertheless a target such as M31 seems promising in so far as a special signature is expected: as it is a spiral galaxy tilted with respect to the line of sight, we expect more lensing events in the far side of the disk, which lies behind a larger part of M31’s halo.

6. What’s next?

In a first step we have to check on a larger sample of pictures that we can reach the required photometric accuracy.

Then we could reanalyze the data of ongoing experiments following our approach. If we are right, the important gain in statistics will allow to put constraints on the brown dwarf distribution in the halo.

Our simulation show that significant improvements in efficiency can be obtained in several ways:

All our estimates have been made with a seeing of 2” where 17% of the starlight reaches the pixel at the center of the seeing spot. For a seeing of 1”, 50% of the starlight reaches this pixel, and our sensitivity then increases because the required amplifications are smaller. First estimates indeed indicate an enhancement of a factor 2 for the LMC and 5 for M31 with a seeing of 1”.

To increase the sensitivity to larger brown dwarf masses one will have to resort to multi-field procedures. Note that M31 seems a better target in this respect (see figure 3). To support our conclusions we plan to make test experiments on M31, using the Pic du Midi or CERGA telescopes.

On the other hand for small masses the shape of the amplification curve will be difficult to observe as most events will last about 24 hours but will be observed only during the night. This difficulty could be overcome by correlating observations of telescopes in faraway sites.

On the basis of the above remarks, we have to define an optimal observation device. As an alternative to the CCD camera one can use of a photomultiplier array,
which has a far better photometric precision, but at the expense of a poorer angular resolution\(^{20}\).

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