The Masses of Nearby Dwarfs Can Be Determined with Gravitational Microlensing

by

B. Paczyński

Princeton University Observatory, Peyton Hall, Princeton, NJ 08544-1001, USA
Visiting Scientist, National Astronomical Observatory, Mitaka, Tokyo, 181, Japan
e-mail: bp@astro.princeton.edu

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ABSTRACT

Microlensing of distant stars in the Milky Way by nearby high proper motion stars offers a direct way to precisely measure the masses of single lower main sequence stars and brown dwarfs.

Key words: gravitational lensing – Stars: low mass, brown dwarfs

Gravitational microlensing can be used to determine the masses of lensing objects, as the time scale of the event is proportional to the square root of the lensing mass. Unfortunately, the time scale also depends on the distance to lens and source and their relative transverse motion, making the mass determination rather uncertain (cf. Paczyński 1991 and references therein). In the special case of compact masses located in a globular cluster and lensing distant stars, the mass determination may be more robust, but the expected rate of events is very low (Paczyński 1994). In this paper another possibility of accurate determination of microlensing masses is presented.

Every high proper motion star must be nearby and may have its parallax measured from the ground with a precision approaching a milliarcsecond (Gatewood 1987, Monet 1992). According to Luyten (1976) the number of high proper motion stars in the whole sky which are brighter than $\sim 15$th magnitude is $N \approx 500 \cdot (1''/\mu p m)^3$ (where $\mu p m$ is the annual proper motion). The scaling would be exact if all stars with a given proper motion could be detected and measured, irrespective of their magnitude, as for a given linear velocity the distance scales as $\mu p m^{-1}$, and the volume and the number of stars scales as $\mu p m^{-3}$. The luminosity function is fairly flat at the faint end, so the number of high proper motion stars
brighter than 20th magnitude is likely to be only by a factor of few larger than the number of stars brighter than 15th magnitude. There may be up to $\sim 10$ stars which are brighter than 20th magnitude and which have proper motion in excess of $0''/5/\text{yr}$ on a Schmidt plate which is $\sim 5$ degrees on a side.

It will be very important to conduct a search for the faint high proper motion stars over the whole sky. When combined with the accurate parallax measurements, such a search would provide accurate information about the local luminosity function at the faint end of the main sequence. The amount of work required by such a project is enormous, and it is not clear when it will become feasible, though a tremendous progress is being made in this area (cf. IAU Symposia 156 and 161: Mueller and Kolačzek 1993, MacGillivray et al. 1994). In fact, the DUO collaboration may use their large database of Schmidt images of the Galactic bulge, originally obtained for the search of microlensing events, to search for the faint high proper motion stars (Alard 1995).

The purpose of this paper is to point out that once the very laborious search for faint, high proper motion stars is done, and the objects are found, the follow-up determination of the masses of a large subsample of such objects is a relatively simple and straightforward task using gravitational microlensing. This can be done close to the Milky Way, where a high number density of distant stars provides a convenient background for the microlensing searches. In this case we shall know ahead of time which are the lensing objects, and their astrometry will make it possible to predict when the microlensing events will occur.

Current CCD searches for gravitational microlensing allow the brightness determination for up to 120,000 stars in a field of $15' \times 15'$ (Udalski et al. 1994), i.e., $\sim 0.15$ stars per square arcsecond. This number depends on the seeing and can be made a factor of few larger under excellent seeing conditions. For the purpose of this paper we shall assume that the number of measurable stars may be as large as 0.3 per square arcsecond. Most of these stars are at a distance of a few kiloparsecs (Paczyński 1964, Paczyński et al. 1994).

A high velocity star is likely to be at a distance of a few tens of parsecs. Let us consider it to be a lens with a mass $M$ at a distance $D_d$, with one of the background stars being a source at a distance $D_s$. The angular radius of the Einstein ring can be calculated as (cf. Paczyński 1991, Eq. 4)

$$\varphi_E = \left[ \frac{4GM}{c^2} \frac{D_s - D_d}{D_d D_s} \right]^{1/2} = 0''0090 \times \left( \frac{M}{0.1\text{M}_\odot} \frac{10\text{ pc}}{D_d} \right)^{1/2} \left( 1 - \frac{D_d}{D_s} \right)^{1/2}. \quad (1)$$

Let the proper motion of the nearby star be $\dot{\varphi}$. The area in the sky covered by it with its Einstein ring in time $t$ can be calculated as

$$S = 2\varphi_E \dot{\varphi} t = 0.018 \left( 1'' \right)^2 \left( \frac{M}{0.1\text{M}_\odot} \frac{10\text{ pc}}{D_d} \right)^{1/2} \left( 1 - \frac{D_d}{D_s} \right)^{1/2} \left( \frac{\dot{\varphi}}{1'' \text{yr}^{-1}} \right) \left( \frac{t}{1\text{yr}} \right). \quad (2)$$

Combining the area given by Eq. (2) with the number density of background stars estimated at 0.3 per square arcsecond we find that a typical time interval between
microlensing events is somewhat less than one per century for any given high proper motion star. This means that we need at least a few hundred of them to detect a few microlensing events per year.

The photometric measurements of microlensing induced time variations give the value of the event time scale defined as

\[ t_0 \equiv \frac{\varphi E}{\varphi}, \]

and the mass of the lens follows directly from Eqs. (1) and (3) as

\[ M = 0.124M_\odot \left( \frac{\dot{\varphi} t_0}{0^\prime 01} \right)^2 \left( \frac{D_d}{10 \text{ pc}} \right) \left( 1 - \frac{D_d}{D_s} \right)^{-1}. \]

Note, that all the important quantities on the right hand side of Eq. (4) are directly measurable: \( \dot{\varphi}, t_0, \) and \( D_d. \) The value of \( D_s \) is less important, as we expect \( D_d/D_s \sim 10^{-2}, \) and even a crude estimate will be adequate.

It is interesting that if the distance to the lensing star is measured using the standard method of a relative parallax with respect to the source star, then the distance which is measured this way, \( d_\pi, \) is related to the true distance \( D_d \) with the equation

\[ \frac{1}{d_\pi} = \frac{1}{D_d} - \frac{1}{D_s}. \]

Now the Eq. (4) may be written as

\[ M = 0.124M_\odot \left( \frac{\dot{\varphi} t_0}{0^\prime 01} \right)^2 \left( \frac{d_\pi}{10 \text{ pc}} \right), \]

and this contains only the directly measurable quantities.

The only technical problem with the microlensing is the difficulty of achieving high photometric accuracy in dense stellar fields, but this technology is rapidly maturing (cf. Udalski et al. 1994, Alcock et al. 1995). The proposed program is photometrically much easier than the current massive microlensing searches, as the location and time of each event can be predicted ahead of time, pretty much like stellar occultations by asteroids.

The proposed project refers to visible, though faint, high proper motion objects, which are expected to be mostly low mass M dwarfs or relatively young brown dwarfs. However, if all these could be monitored photometrically on a sustained basis then microlensing events due to dark companions might be discovered. This is a much more difficult task, as such events would come at unpredictable time. In particular, the detection of lensing by planetary companions would require photometric sampling at about one hour intervals.

The photometrically measured time scale of a microlensing event, \( t_0, \) is sufficient to uniquely determine the mass of a single lensing star or a brown dwarf. Perhaps 1% precision in the mass determination can be achieved, as very accurate
photometry (to obtain $t_0$), and astrometry (to obtain $d_\pi$) are possible, at least in principle. If an angular resolution of $\sim 0.005'$ is achieved with the future imaging interferometers then an independent astrometric determination of the size of the Einstein ring, and therefore the lens mass, will be possible by means of precise monitoring the relative location of the lens and the two micro-images, which have an expected separation of the order of $0.02'$, as given with the Eq. (1). Note, that current ground based infrared imaging achieves the resolution of $\sim 0.2'$ (Eckart et al. 1993). Even higher resolution is possible with the Hubble Space Telescope. Still higher resolution is possible with adaptive optics and imaging interferometry (cf. Shao and Colavita 1992, Beckers 1993, Robertson and Tango 1994, Roddier 1995, Shao 1995, and references therein, Tomkin et al. 1995).

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