

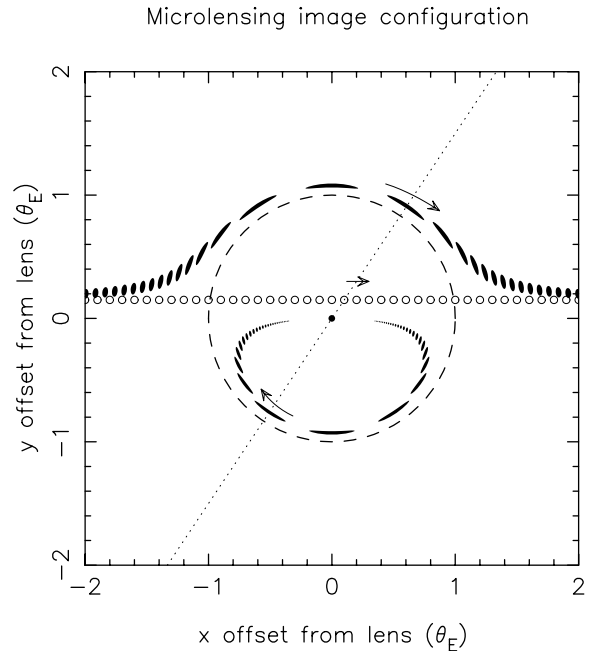
## Microlensing

Microlensing refers to the special case of GRAVITATIONAL LENSING where the multiple images produced are too close together on the sky to be observed as separate images. However, the lensing can still be detected because these multiple images appear as a single object of increased apparent brightness. Although this is not detectable in a one-off observation (since we do not know the ‘normal’ brightness of the source), with the passage of time the lens moves across the Earth–source line and the amount of brightening changes. Typically the source will appear to brighten, reach a maximum and then fade symmetrically back to normal over the course of a few weeks or months; this is called a ‘microensing event’.

The major application of microensing, suggested by Paczynski in 1986, is in the search for the DARK MATTER which is strongly believed to exist from rotation curves of spiral galaxies etc. Since the lensing effect depends only on lens mass, it can be used to search for very faint or invisible objects such as brown dwarfs, neutron stars, old white dwarfs or black holes, which might make up the dark matter. These are collectively known as massive compact halo objects or MACHOs, in contrast to the hypothetical weakly interacting massive particles or WIMPs.

To understand the basics of microensing, consider a small massive object (the lens) situated exactly on the line of sight from Earth to a background star and consider a number of light rays radiating from the star passing the lens at different distances and being bent towards the lens. Since the bending angle for a light ray increases with decreasing distance from the lens, it is clear that there is a unique ‘miss distance’ such that the ray will be deflected just enough to hit the Earth; this distance is called the Einstein radius. By rotational symmetry about the Earth–star axis, an observer on Earth with perfect resolution would see the star lensed into an annulus centered on its ‘true’ position, called an Einstein ring. As the lens is moved slightly off the line of sight (e.g. by 0.1 Einstein ring radii), the Einstein ring splits into two banana-shaped arcs, one on the same side of the lens as the source, one on the opposite side. As the lens moves further off (more than 1 Einstein radius), the arcs become more circular, the ‘opposite-side’ arc fades very rapidly and the ‘same-side’ arc turns into a slightly deflected and nearly circular image of the star. Figure 1 illustrates a sequence of such images for a typical microensing event.

Although the perfect alignment giving the Einstein ring will rarely occur in practice, it is still a very important concept because the size of the hypothetical Einstein ring sets the length scale over which substantial brightening will occur. As we will see, for a typical lens in our Galaxy the radius of the Einstein ring  $r_E$  is roughly  $8(M/M_\odot)^{1/2}$  AU (astronomical units), where  $M$  is the lens mass. Knowing this scale allows us to understand most of the general characteristics of microensing: it is extremely small compared with the typical distance to a lens, so the angular separation of the two images will be too



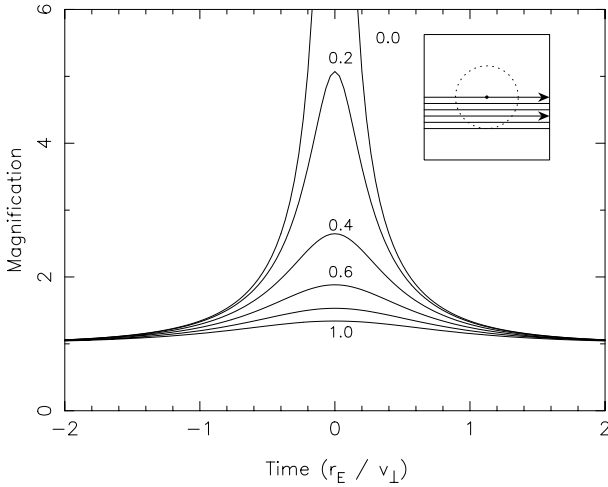
**Figure 1.** A microensing event seen at ‘perfect’ resolution. The axes show angular offsets on the sky from the lens (central dot) in units of the Einstein angle; the dashed circle is the Einstein ring. The series of small open circles shows the ‘true’ source position at successive timesteps. For each source position, there are two images (solid blobs) collinear with the lens and source, as indicated by the dotted line; the arrows illustrate their motion.

small to resolve, hence the ‘micro’lensing. However, it is considerably larger than either the size of a star or the size of a MACHO, so we can usually approximate the lens and source as pointlike, which leads to a simple prediction for the lightcurve shape. Also,  $r_E$  is very small compared with the typical separation of objects in the Galaxy, which implies that microensing will be a very rare phenomenon. Another notable feature is that  $r_E$  is proportional to the square root of the lens mass. This means that the area of sky ‘covered’ by a lens (at fixed distance) is proportional to its mass, so the total fraction of sky covered depends only on the total mass density in lenses, not the individual lens masses. This fraction is called the ‘optical depth’  $\tau$ , and is  $\sim 10^{-6}$  for Galactic microensing. The duration for a microensing event is given by the time for the lens to move by  $2r_E$  relative to the Earth–star line; for typical Galactic speeds of  $200 \text{ km s}^{-1}$ , this is  $\sim 130 \text{ days} \times (M/M_\odot)^{1/2}$ .

For perfect alignment, simple geometry gives the (small) deflection angle of the light ray meeting Earth as  $\alpha = r_E/D_{ol} + r_E/D_{ls}$ , where  $D_{ol}$  is the observer–lens distance,  $D_{ls}$  is the lens–source distance etc. Requiring this to equal the general relativity deflection,  $\alpha = 4GM/c^2 r_E$ , we obtain

$$r_E = \left( \frac{4GM}{c^2} \frac{D_{ol} D_{ls}}{D_{os}} \right)^{0.5}$$

The angular Einstein radius is just  $\theta_E \equiv r_E/D_{ol}$ . If we now introduce a small offset of the lens by a distance  $b$  from



**Figure 2.** Microlensing event lightcurves (magnification versus time) for six values of the impact parameter  $u_{\min} = 0.0, 0.2, \dots, 1.0$  as labelled. Time is in units of the Einstein radius crossing time  $r_E/v_{\perp}$ . The inset illustrates the Einstein ring (dotted circle) and the source paths relative to the lens (dot) for the six curves.

the Earth–source line, i.e. an angle  $\beta \equiv b/D_{\text{ol}}$ , a simple generalization gives the two image angular positions (relative to the lens) as

$$\theta_{\pm} = 0.5[\beta \pm (\beta^2 + 4\theta_E^2)^{1/2}].$$

Since lensing preserves surface brightness, the magnification  $A_i$  of each image is given by the ratio of image to source areas, which for a ‘small’ source and any axisymmetric lens is just

$$A_i = \left| \frac{\theta_i}{\beta} \frac{d\theta_i}{d\beta} \right|.$$

For a point lens, this leads to a total observed magnification as the sum of the two image magnifications,

$$A = A_+ + A_- = \frac{u^2 + 2}{u(u^2 + 4)^{1/2}} \quad (1)$$

where  $u \equiv \beta/\theta_E = b/r_E$  is the misalignment in units of the Einstein radius. This behaves as  $A \approx u^{-1}$  for  $u \lesssim 0.5$ , so the magnification may be large, but as  $A \approx 1 + 2u^{-4}$  for  $u \gtrsim 2$ , so the magnification rapidly becomes negligible at large  $u$ . For uniform motions, we will have  $u(t) = \{u_{\min}^2 + [v_{\perp}(t - t_0)/r_E]^2\}^{1/2}$  where  $v_{\perp}$  is the transverse velocity of the lens relative to the line of sight and  $u_{\min}$  is the value of  $u$  at closest approach, which occurs at time  $t_0$ . Substituting this into equation (1) gives the lightcurve  $A(t)$ ; some examples are shown in figure 2.

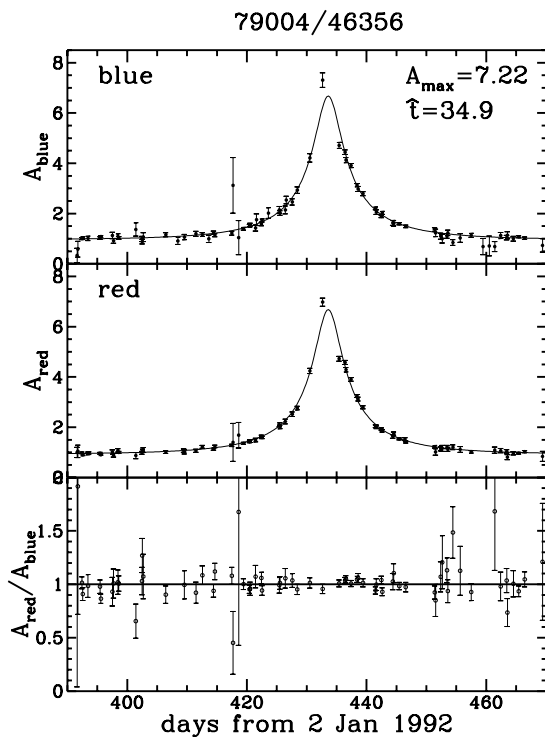
### Observations of microlensing

To search for microlensing by MACHOs, since it is so rare we need millions of source stars and they should

be far enough away to give a good path length for lensing, but not so far away that the individual stars are faint. The obvious targets for dark-matter lenses are the LARGE MAGELLANIC CLOUD (LMC) and SMALL MAGELLANIC CLOUD (SMC), the largest of our Milky Way’s many satellite galaxies, since the sight line to them passes mainly through the Galactic halo. The Galactic bulge is also an interesting target, although here because of the high stellar density the microlensing should be mainly due to intervening faint stars rather than dark matter. Around 1991, several teams of astronomers called MACHO, EROS and OGLE began large projects using wide-field 1 m class telescopes to search for microlensing events. The novel feature of these experiments is their massive data volume, requiring large amounts of disk and tape storage and special high-speed photometry programs. The expected number of microlensing events is much smaller than the fraction of intrinsic variable stars, but fortunately microlensing has many strong ‘signatures’ that are distinct from all previously known types of variable star: the most important is the ‘uniqueness’, i.e. any given star should be microlensed at most once in a human lifetime, while almost all variable stars are periodic or quasi-periodic. Also, most events should have a symmetrical shape as in figure 2, and they should be achromatic (the source’s color should not change during the event), since lensing is independent of wavelength.

The MACHO, EROS and OGLE teams announced their first candidate microlensing events near simultaneously in late 1993 (figure 3). Since then, they have accumulated much more extensive datasets, and completed detailed calculations of their microlensing detection efficiency as a function of event duration; thus a number of general results have become clear.

- (i) Hundreds of events have been observed towards the Galactic bulge. They are distributed ‘randomly’ across the color–magnitude diagram, and their distribution of peak magnifications matches the theoretical prediction, which provides a very convincing check that microlensing works as predicted and that the experiments can detect it. The event rate towards the bulge is greater than initially predicted by Galactic models, favoring a barred structure for the Galaxy. The distribution of timescales is consistent with most of the lenses being low-mass stars as expected and can provide constraints on the stellar mass function at low masses.
- (ii) Towards the Magellanic Clouds, no ‘short’ events (timescales from a few hours up to 20 days) have been seen by any group. This places strong limits on ‘Jupiters’ in the dark halo: specifically, compact objects in the mass range  $10^{-6}$ –0.05 solar masses contribute less than 10% of the dark matter around our Galaxy. This is a very important result, as these objects were previously thought to be the most plausible form of baryonic dark matter, and (for masses below 0.01 solar masses) they would have been virtually impossible to detect directly.



**Figure 3.** The first LMC microlensing candidate from the MACHO project. (Expanded view: 6 yr of constant data are outside the plot). Upper and middle panels show brightness versus time in blue and red passbands respectively, in units of the baseline value. Points with error bars are observations, the curve is the best microlensing fit. The lower panel shows the ratio of red/blue flux, illustrating the lack of color change.

- (iii) Approximately 18 events with durations 30–200 days have been observed towards the Magellanic Clouds. The implied optical depth is well above expectation from ‘known’ stars, and is roughly 1/3 of the value expected ( $\tau \approx 5 \times 10^{-7}$ ) for an all-MACHO dark halo. The relatively long durations imply lens masses of roughly 0.3–0.7 solar mass, which is a puzzle as discussed below.
- (iv) Many events are now detected in real time and announced on the world-wide web. This enables more frequent monitoring of ongoing events, giving more precise tests of the shape. This has attracted considerable interest since, where the lens is a low-mass star (probably the case for most of the events towards the Galactic bulge), a planet around the lens star may give rise to a short-duration ‘blip’ superimposed on the smooth microlensing lightcurve: this method is potentially sensitive to low-mass planets down to a few Earth masses, below the range accessible to radial-velocity planet searches. Two groups called PLANET and MPS are now searching for this effect.

### Current questions in microlensing

The nature of the objects giving rise to the lensing towards the Magellanic Clouds is a significant puzzle at present; the inferred lens masses are well above  $0.1M_{\odot}$ , which means that they cannot be ordinary hydrogen-burning stars in a spherical halo, as these would be visible in large numbers in deep images, e.g. the Hubble Deep Field. There are two classes of solution: either the lenses are in the halo but are much fainter, e.g. old white dwarfs or possibly primordial black holes, or they are low-mass stars but in a non-halo population, i.e. preferentially concentrated in the foreground of the LMC. The white-dwarf solution has significant problems associated with early metal production but has received some support recently from a possible detection of proper motions of faint objects in the HUBBLE DEEP FIELD. Various classes of non-halo population have been proposed, e.g. a ‘thick’ LMC disk, a small dwarf galaxy projected in front of the LMC, a warped Milky Way disk etc, but several searches for such populations have been negative.

There are several ways of testing these possibilities: one is to measure distances to individual lenses. In a ‘standard’ microlensing event as in figure 2 it is impossible to measure the lens distance since the one physical parameter (event duration) depends on three unknowns, the lens mass, distance and transverse velocity. However, as proposed by Gould and others, a small fraction of observed events should deviate from the standard shape for one of several reasons: the non-uniform motion of the Earth, the finite size of the source, a binary lens etc. In these cases we can obtain an additional observable which constrains the location of the lens. At present there are only one or two such cases for Magellanic Cloud lensing. Future satellite observations may help to measure lens distances, either by measuring the ‘parallax’ effect or the small centroid shift during the event.

Another active area is the search for microlensing towards the ANDROMEDA GALAXY, M31. This is considerably more challenging since the greater distance means that there are multiple unresolved stars per resolution element, and sophisticated image differencing techniques are necessary. However, it has the advantage that microlensing from M31’s own halo will produce substantially more events towards the far side of M31’s disk than towards the near side, owing to the nearly edge-on inclination. Two groups called AGAPE and MEGA have done pilot studies and are currently undertaking large-scale searches towards M31.

### Cosmological microlensing

Although microlensing within the LOCAL GROUP is the main application at present, microlensing of ‘point’ sources at cosmological distances (e.g. quasars, supernovae or gamma-ray bursts) may also be observable. In the case of a quasar lensed into multiple images by a foreground galaxy, the individual stars in the galaxy may act as microlenses. Here the microlensing appears as brightness changes unique to one image of the multiplet (after correcting for

the time delay); in this case the optical depth is typically close to unity (because the surface density must be of order the 'critical' surface density to produce multiple imaging), so the interpretation of the lightcurve is complex. Other searches are in progress for microlensing of quasars behind the VIRGO CLUSTER by dark objects in the cluster, and the Next Generation Space Telescope should be easily able to detect microlensing of stars in the Virgo galaxy M87.

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Searches on NASA ADS or xxx.lanl.gov for the various team acronyms should locate recent papers.

*Will Sutherland*