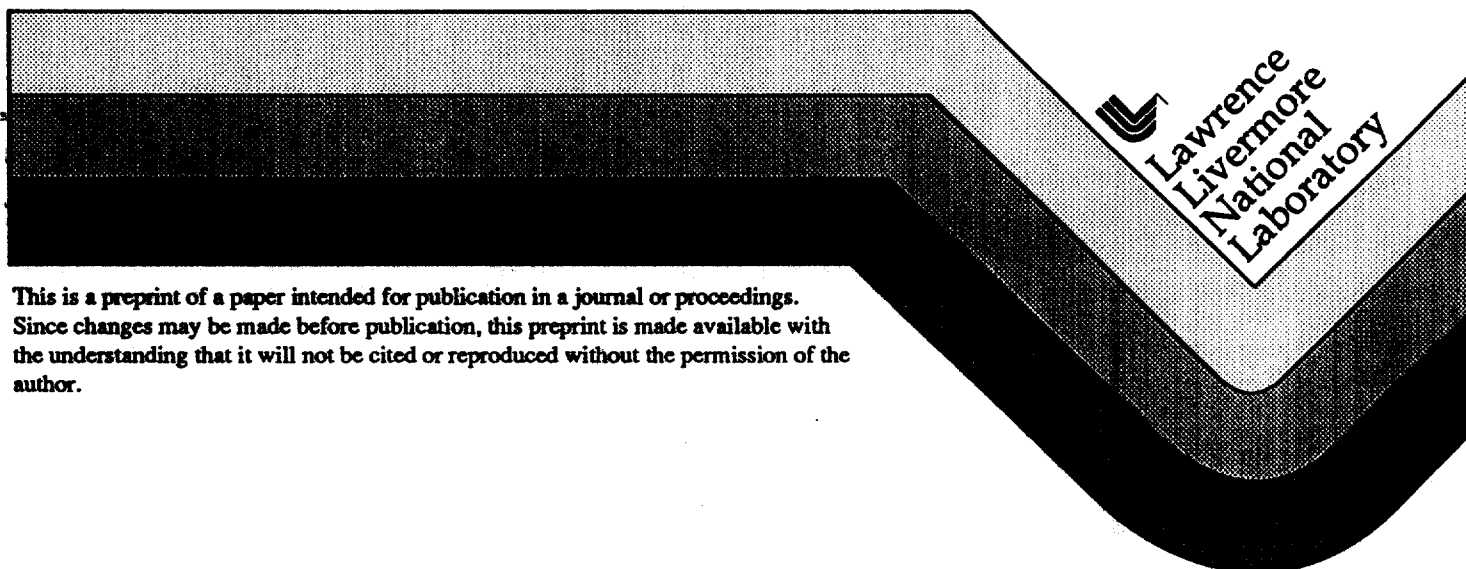# Gravitational Microlensing Results from MACHO

C. Alcock, R. A. Allsman, D. R. Alves, T. S. Axelrod, A. C. Becker, D. P. Bennett, K. H. Cook, K. C. Freeman, K. Griest, J. A. Guern, M. J. Lehner, S. L. Marshall, B. A. Petersen, M. R. Pratt, P. J. Quinn, A.W. Rodgers, C. W. Stubbs, W. Sutherland, and D. L. Welch

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# GRAVITATIONAL MICROLENSING RESULTS FROM MACHO

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The MACHO project is searching for dark matter in the form of massive compact halo objects (Machos), by monitoring the brightness of millions of stars in the Magellanic Clouds to search for gravitational microlensing events. Analysis of our first 2.3 years of data for 8.5 million stars in the LMC yields 8 candidate microlensing events, well in excess of the $\approx$ 1 event expected from lensing by known low-mass stars. The event timescales range from 34 to 145 days, and the estimated optical depth is $\sim 2 \times 10^{-7}$, about half of that expected from a 'standard' halo. Likelihood analysis indicates the typical lens mass is $0.5^{+0.3}_{-0.2} M_\odot$, suggesting they may be old white dwarfs.

## 1 Introduction

Since this is the first microlensing talk at a meeting comprising a majority of particle physicists, we will provide a short introduction to microlensing before describing the main results from the MACHO project.

The field of microlensing has undergone a dramatic expansion in the few years since the first candidates were discovered, and there are now a large number of results towards both the LMC and the Galactic bulge; detailed reviews are provided by refs.[1,2]. Updated information on the MACHO project, and links to other microlensing projects are available on our WWW site[3].

In §2 we discuss the motivation for Macho searches, in §3 we outline the basics of microlensing, and in the remainder of the paper we summarise the MACHO project, focusing on recent results from the 2-year LMC data.

## 2 Motivation

While the most popular theories of galaxy formation involve a universe dominated by non-baryonic dark matter, we should keep in mind that there are really two dark matter problems, as emphasised by e.g. Turner[4]; the 'first' dark matter problem is that baryon density inferred from primordial nucleosynthesis $\Omega_B \sim 0.02 - 0.08$ is greater than that observed in stars and gas $\Omega_{vis} \lesssim 0.01$. The 'second' dark matter problem is that the matter density

inferred from galaxy clusters and large-scale streaming motions is $\Omega_{\rm dyn} \gtrsim 0.2$ which is greater than $\Omega_B$. This suggests that the universe contains both baryonic and non-baryonic dark matter.

If large numbers of unseen baryons exist, the most natural place for them to hide is as compact objects in the halos of galaxies; hence the generic name 'massive compact halo objects' or Machos. A wide variety[5] of Macho candidates have been proposed; these include 'brown dwarfs' which are balls of H and He below the minimum mass $\sim 0.08\,{\rm M_\odot}$ for fusion to occur; stellar remnants such as white dwarfs or neutron stars; and black holes, which may be either primordial or remnants. Even if Machos are abundant, they would be very hard to detect directly; some types of Macho such as brown dwarfs at $\gtrsim 0.01\,{\rm M_\odot}$ or old white dwarfs may soon be constrained by deep surveys in near-IR wavebands, but Jupiter-mass brown dwarfs or black holes would be almost impossible to detect directly.

In a classic paper, Paczynski[6] proposed that Machos could be detected by their gravitational 'microlensing' influence on the light from distant stars; this led directly to the first generation of microlensing searches (EROS-1, MACHO and OGLE) which started observations in the early 1990's and turned up the first microlensing candidates in 1993. More recently, several new projects are underway, including DUO, EROS-2[7], MOA, AGAPE and Vatt-Columbia.

## 3 Microlensing

The principle of microlensing is simple; if a compact object lies near the line of sight to a background star, the well-known GR light deflection occurs, and two images of the star are formed on opposite sides of the lens. For galactic scales, the angular splitting of these images is $\sim 0.001$ arcsec which cannot be resolved at present (hence 'microlensing'); but the two unresolved images combine to increase the apparent brightness of the source. The characteristic length-scale is the 'Einstein radius'

$$r_E = \sqrt{\frac{4GmLx(1-x)}{c^2}} \tag{1}$$

where $m$ is the lens mass, $L$ is the source distance and $x$ is the ratio of the lens and source distances. For a source in the LMC at $L = 50\,{\rm kpc}$ and a lens at $10\,{\rm kpc}$, $r_E \approx 10^9\,{\rm km}\,\sqrt{m/{\rm M_\odot}}$; since this is much larger than a typical star or Macho, in most cases we may assume a point source and point lens, and the resulting magnification is simply[8]

$$A = \frac{u^2 + 2}{u\sqrt{u^2 + 4}} \tag{2}$$

where $u = b/r_E$ and $b$ is the distance of the lens from the undeflected line of sight. For $u \lesssim 0.5$, $A \approx u^{-1}$, so the magnification may be large; while it drops rapidly as $A \approx 1 + 2u^{-4}$ for $u \gg 1$.

Of course, a constant magnification is not detectable since we don't know the intrinsic brightness of the source; but due to the relative motion of observer, lens and source, the magnification is transient with a duration

$$\hat{t} \equiv 2r_E/v_\perp \sim 130 \sqrt{\frac{m}{M_\odot}} \text{ days,} \tag{3}$$

where $v_\perp \sim 200\,\mathrm{km\,s^{-1}}$ is the transverse velocity of the lens relative to the line of sight. This is a convenient timescale for astronomical observations. Also, the dependence $\propto \sqrt{m}$ means that by monitoring on a range of timescales, the experiment may be sensitive to a wide range of masses from $\sim 10^{-7}\,M_\odot$ to $\sim 100\,M_\odot$, covering most of the popular Macho candidates. This mass range is set at the low end where $r_E$ is smaller than the size of a typical star and large magnifications cannot occur; and at the high end where the event duration exceeds the few-year duration of a typical experiment. (Other lensing techniques are sensitive to different mass ranges; e.g. VLBI searches for macrolensed quasars, and searches for microlensing of quasars[9] or perhaps gamma-ray bursts).

### 3.1 Optical Depth

Since $r_E \propto \sqrt{m}$, the solid angle subtended by a lens at a given distance is $\propto m$; thus, the probability that a random star is microlensed with $u < 1$ or $A > 1.34$ at any instant depends on the mass density of lenses $\rho(l)$ along the line of sight, but not their individual masses. This probability is called the 'optical depth' $\tau$, and is given by

$$\tau = \frac{4\pi G}{c^2} \int_0^L \rho(l) \frac{l(L-l)}{L} dl \tag{4}$$

By the virial theorem, it is easily shown that $\tau \sim v^2/c^2$ where $v$ is the orbital velocity of the Galaxy. More detailed calculations[10] give an optical depth towards the Large Magellanic Cloud of

$$\tau_{\mathrm{LMC}} \approx 5 \times 10^{-7} \tag{5}$$

for an all-Macho halo of 'standard' form. (This number is uncertain by perhaps 50% due to uncertainties in the halo model. However, as a reasonable approximation it scales proportional to the halo mass inside $50\,\mathrm{kpc}$; it is not

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too sensitive to the halo flattening or core radius). Note, however, that the event rate $\Gamma$ does depend on the lens masses $\propto m^{-0.5}$, because

$$\Gamma = 4\tau/\pi\langle\hat{t}\rangle \approx 1.6 \times 10^{-6}\,(m/\,M_\odot)^{-0.5}\text{ events/star/year} \qquad (6)$$

i.e., low-mass Machos produce (relatively !) numerous short events whereas massive Machos produce fewer long-lasting events.

The very low optical depth is the main difficulty of the experiment; only one star in two million will be magnified by $A > 1.34$ at any given time, while the fraction of intrinsic variable stars is much higher, $\sim 0.3\%$. Fortunately, microlensing events have many strong signatures which are different from all currently known types of stellar variability. Assuming a single point source and lens, and uniform motions, the events should have a symmetrical shape given by eq. (2) and $u(t) = [u_{min}^2 + ((t - t_{max})/0.5\hat{t})^2]^{0.5}$, they should be achromatic, and at most one event should be seen in any given star since the probability is so low.

In reality, various deviations may occur due to e.g. blending of the source star with other unresolved stars, a binary lens or source, the non-uniform motion of the Earth, or the finite size of the source; but the above form should be a good approximation for most events.

If many events are found, several statistical checks can also be made; allowing for the detection efficiency, the events should be randomly distributed across the colour-magnitude diagram, the distribution of peak magnifications should correspond to a uniform distribution in $u_{min}$, and the event timescales and peak magnifications should be uncorrelated.

## 4 Observations

Due to the low optical depth, a very large number of stars must be monitored over a long period to obtain significant results. The simplest targets for this search are the Large and Small Magellanic Clouds, the largest of the Milky Way's satellite galaxies, since they have a high surface density of stars, they are distant enough at 50 and 60 kpc to provide a good path length through the dark halo, and they are located 30° and 45° from our galactic plane, so the density along the line of sight is dominated by dark matter. We also observe the Galactic Bulge when the LMC and SMC are too low in the sky.

Since mid-1992, the MACHO collaboration has had full-time use of the 1.27-m telescope at Mt. Stromlo Observatory near Canberra, Australia; an extended run until 1999 has recently been approved. Details of the telescope are given by ref. [11], and of the camera system by ref. [12]. Briefly, an optical corrector gives a field of view of $0.7 \times 0.7$ degrees, and a dichroic beamsplitter

is used to take simultaneous images in red and blue passbands. The two foci are equipped with very large CCD cameras, each containing 4 CCD chips of $2048 \times 2048$ pixels. The typical exposure time is 300 sec, and about 60 images are taken per clear night; we took our 50,000th image in October 1996. All the 4 TB of raw data is archived to Exabyte tape.

A special-purpose code [14] is used to measure the brightness of all stars in the images; briefly, one good-quality image of each field is used to define a 'template' list of stars. Each subsequent image is aligned with the template using bright reference stars, and a point spread function (PSF) is estimated from these. Then, the flux of all stars is estimated using the known positions and PSF; this provides a dramatic time saving as well as more accurate results. The reductions take around 1 hour per image on a Sparc-10.

Since late 1994 we have implemented same-day processing for a large fraction of our fields, which enables us to detect events in real time [15,16].

Just to mention our Galactic Bulge results: we have detected over 100 microlensing events towards the bulge [17,16], including several events due to binary lenses and one showing asymmetry due to the Earth's orbit [18]. Although the lensing towards the bulge is probably dominated by low-mass stars rather than dark matter, this has interesting consequences for Galactic structure, as well as providing a very nice proof of microlensing.

## 5   LMC Results

We have recently completed an analysis [19] of the first 2.3 years of data for 22 well sampled LMC fields; this comprises over 8 million stars with 300 to 800 observations each. We select microlensing candidates using a set of objective selection criteria. The most important of these are that the star should have a brightening of high significance, with peak magnification $A_{\mathrm{max}} > 1.75$, and that its flux should be approximately constant outside this region. [These selection criteria have been modified since the first year's LMC analysis [14], due in part to experience with the bulge events. Briefly, we have relaxed the cuts on the 'standard' microlensing shape, achromaticity and stellar crowding, but we now require higher significance and magnification; thus, the 'marginal' events 2 & 3 from refs. [13,14] do not pass the new cuts, but some new first-year events appear.]

We find 12 objects in the 2-year dataset passing the final cuts, of which 4 correspond to 2 stars doubly detected in field overlaps, and 2 are rejected due to 'magnification bias' in that they were brighter than normal in the template image and then faded below our detection limit (one of these was superposed on a background galaxy, and was almost certainly a supernova). Thus we

have 8 microlensing candidates, with timescales from 34 to 145 days, shown in Figure 1; they are numbered 1, 4-10 to avoid ambiguity. Of these eight candidates, six are well fitted by the standard microlensing shape; three of them (numbers 5, 7 and 9) show evidence of chromaticity, but this is found to be consistent with blending [19]. Event 9 shows a distinctive double-peaked structure and is clearly [20] due to a binary lens. [a] Event 10 is somewhat asymmetrical and may be a variable star, though it could also be microlensing of a binary source star. The inclusion or exclusion of this event has little influence on the results.

We are confident that most of our 8 candidates are genuine microlensing events; they cannot be due to observational error, cosmic ray hits, satellite trails etc. since they are seen at different pixel locations (due to pointing variations) in dozens of independent CCD frames; event 1 was confirmed by EROS, and event 4 was detected in real-time and observed with other telescopes.

Intrinsic stellar variability is more difficult to exclude, but several of the candidates have high magnifications, event 9 is very characteristic of a binary lens, and event 4 was observed spectroscopically and appeared normal. The distribution of peak magnifications and in the colour-magnitude diagram is consistent with expectation [19]. This test also suggests that at least 5 of the candidates are genuine microlensing, since if *only* the 'high-quality' candidates (e.g. 1,4,5 and 9) were microlensing, the distribution of $A_{max}$ would be somewhat improbable [19].

## 6 Implications

In order to derive quantitative results, we clearly need to know our detection efficiency. We have evaluated this using a series of Monte-Carlo simulations; these include the addition of artificial stars at a range of magnifications into real data frames, and also incorporate the known times of observations incorporating bad weather, variable seeing conditions etc. Simulated microlensing events are then processed through our standard software to give the detection efficiency as a function of the event timescale, $\mathcal{E}(\hat{t})$, shown in Figure 2.

It is convenient to show the expected number of events assuming that all the halo is made of Machos with a unique mass $m$; this is given for a standard halo model in Figure 3a. There are two competing effects: for larger

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[a] A binary lens can produce a great diversity of possible lightcurves [21]. However, 'caustic crossings' are generic features; these occur where the number of images changes from 3 to 5 or vice versa, and the magnification becomes large when the source is just inside the caustic. Since the caustic(s) are closed curves in the source plane, caustic crossings must occur in inward/outward pairs.
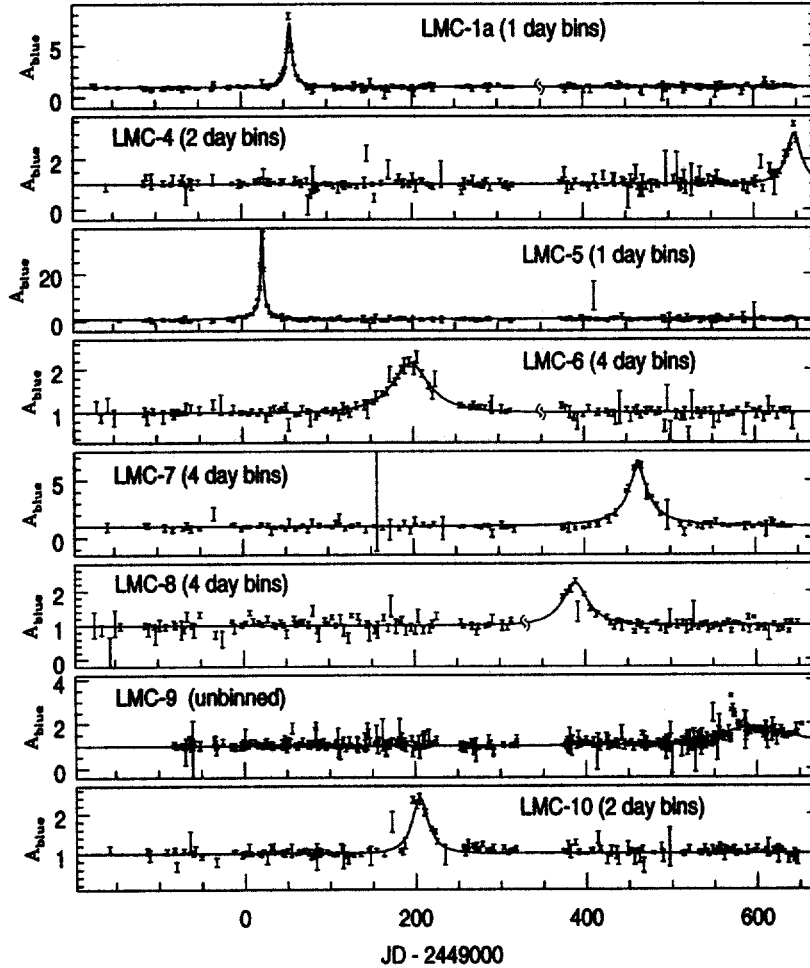
## MACHO LMC 2-year Events



Figure 1: Lightcurves of the 8 candidate events from the 2-year LMC data. Flux measurements (one colour) are plotted in linear units with $1\sigma$ errors, averaged in time bins (see labels) for clarity, and normalised to the fit baseline for each star. The curves show the single-lens microlensing fit. Time is in days.
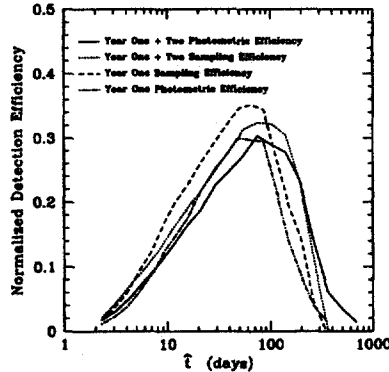
Figure 2: The solid line shows the microlensing detection efficiency (relative to event rate with $u_{min} < 1$) for LMC 2-year sample.

masses $m \gtrsim 0.01\,M_\odot$, most events have timescales $\hat{t} \gtrsim 10$ days where our efficiency is quite good, but the event rate is falling $\propto m^{-0.5}$. For small masses $m < 0.001\,M_\odot$, the theoretical event rate is high but most events are shorter than $\hat{t} \sim 3$ days where our efficiency is low. The product of these two effects gives rise to the peak at $\approx 45$ expected events for $m \sim 2 \times 10^{-3}\,M_\odot$.

## 6.1  Limits on Low-Mass Machos

Although the efficiency is falling towards short event durations, the absence of short events is still very significant, because of the $m^{-0.5}$ factor in eq. 6. From the fact that we have no candidate event with $\hat{t} < 20$ days in the above data, we can conclude that Machos with masses from $6 \times 10^{-5}$ to $0.02\,M_\odot$ contribute less than 20% of the standard halo at 95% confidence. We have extended these limits to lower masses using a separate 'spike' search[22] for very short-timescale events. Some of our fields are observed twice per night, giving a set of 4 data points, two in each passband. We then search for events where all 4 data points on such a night exceed some threshold, while no such deviation occurs in the rest of the light curve. After suitable cuts, we find no such events, and this sets interesting limits on events with durations $\sim 0.3 - 3$ days.

Combining these two analyses, we conclude that Machos in the mass range $10^{-6}$ to $0.02\,M_\odot$ comprise less than 20% of the standard halo; more generally, such objects contribute less than $10^{11}\,M_\odot$ to the halo mass within $50\,\mathrm{kpc}$, as shown in Figure 3b. Similar (nearly independent) limits have been derived by EROS[23].
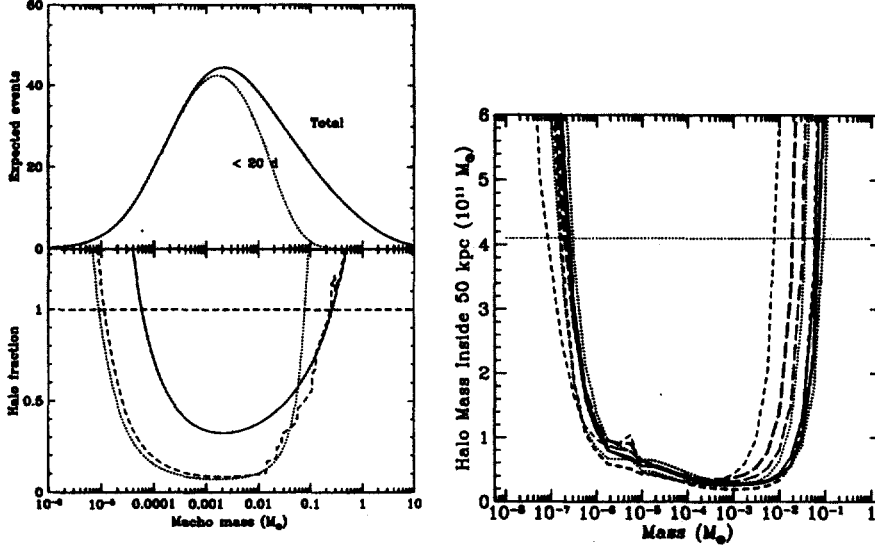
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Figure 3: (a) Upper panel shows expected number of events for all-Macho halo with unique Macho mass $m$. Lower panel shows derived limits on halo Macho fraction. Regions above the curves are excluded at 95% c.l. The solid line is from 8 observed events, the dotted line from no events with $\hat{t} < 20$ days. (b) Upper limits (95% c.l.) on total mass of Machos interior to 50 kpc, from combined 'spike' and standard analysis, for 8 halo models.

## 6.2 Implications of the 8 Events

We can estimate the optical depth via $\tau_{\rm est} = (\pi/4E) \sum_i \hat{t}_i / \mathcal{E}(\hat{t}_i)$, where $E = 1.8 \times 10^7$ star-years is our 'exposure', and $\hat{t}_i$ is the timescale of the $i$-th event. Accounting for our detection efficiency, the 8 events give an estimated optical depth of $\tau_{\rm est} = 2.9^{+1.4}_{-0.9} \times 10^{-7}$, which is just over half of that from an all-Macho dark halo.[b]

For an event with the 'standard' shape, it is not possible to tell where the lens is situated along the line of sight; thus, lensing events can also arise from faint stars in our Galaxy and the LMC[24] itself, as well as halo Machos. However, lensing by known stars is expected to contribute only 1.1 events in this sample, or $\tau_{\rm stars} \sim 0.5 \times 10^{-7}$, so there appears to be a very significant excess [19]. A more conservative estimate of the halo optical depth is given by

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[b] Although the event rate is similar to our earlier estimate (3 candidates in the first year), the new optical depth estimate is considerably higher because events are 'weighted' proportional to their duration, and the new events all have longer timescales.

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excluding event 9 (since the lens may be in the LMC[20]), and event 10 which may be a variable star; this gives $\tau_{halo} = 2.1^{+1.1}_{-0.7} \times 10^{-7}$.

We can estimate the lens masses using the event durations; since one observable $\hat{t}$ depends on three unknowns, the lens mass, distance and transverse velocity, this is only a statistical estimate and is somewhat sensitive to the assumed halo model. For the standard halo, likelihood analysis (Figure 4) gives a most probable lens mass of $0.5^{+0.3}_{-0.2} M_\odot$. If the lenses are in the halo in this mass range, they cannot be hydrogen-burning stars which would be easily detectable[25]. Thus, remnants such as old white dwarfs appear to be a natural possibility. These are not excluded by star-count data, though they must be very faint. White dwarfs also require a rather narrow initial mass function in order to avoid overproducing low-mass stars or supernovae, and may have problems with the high luminosities of the progenitor stars; thus, primordial black holes are a more exotic possibility.
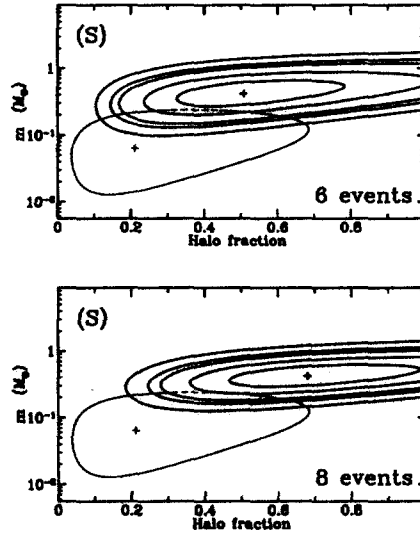


Figure 4: Bold lines are likelihood contours (34,68,90,95,99% enclosed probability) for Macho mass and Macho fraction of the halo, for the standard halo model, for the 8 and 6 event samples. The light line shows the 90% contour from the 1-year analysis.

Although the formal significance of our number of candidates is high, we cannot yet claim a conclusive detection of dark matter; for instance, if a few of our lower-quality candidates were actually variable stars, and the stellar

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lensing rate were double our estimate above, we would still have an excess of events, but the significance would only be marginal. The lensing rate from stars in our own disk is directly constrained by HST star counts; that from stars in the LMC is more uncertain, but is constrained by the line-of-sight velocity dispersion[26], and improved measurements are planned.

Another loophole is that there might be a small dwarf galaxy located between us and the LMC[27]; this could account for most of the observed optical depth, though the *a priori* probability of such an alignment is only $\sim 1\%$.

There are a number of prospects for clarifying these results; we should soon have analysed another 2 years of data, and we will continue observations until 1999; this should give many more events, and also extend the search to longer timescales. The real-time detection system also enables more precise follow-up photometry and spectroscopy to check future candidates; two more real-time LMC events have been discovered during 1996. If most of the lenses reside in the LMC itself, then the events should occur preferentially near the center of the LMC, while halo lensing will produce a more even distribution. Additionally, if the source star is a binary with a period shorter than the event duration ($\sim 10\%$ of events), it is possible to test whether or not the lens is in the LMC[28].

If the lenses are old white dwarfs, they should be accessible to deep searches using the HST or wide-field ground-based imaging. In the longer term, observations from a small satellite in Solar orbit can measure the projected velocity of the lens[29,30], or interferometric measurements could resolve the double images and measure the angular Einstein radius; either one of these measurements can determine whether the lens belongs to the galactic disk, halo or the LMC, and both together would solve for the lens mass, distance and velocity.

In summary, we have found very interesting evidence that Machos in the mass range $0.05 - 1\,M_\odot$ contribute a substantial fraction of our Galaxy's dark matter; continued observations should clarify this in the next few years.

## Acknowledgements

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