Possible gravitational microlensing of a star
in the Large Magellanic Cloud

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There is now abundant evidence for the presence of large quantities of unseen matter surrounding normal galaxies, including our own[1,2]. The nature of this 'dark matter' is unknown, except that it cannot be made of normal stars, dust, or gas, as they would be easily detected. Exotic particles such as axions, massive neutrinos

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or other weakly interacting massive particles (collectively known as WIMPs) have been proposed)[3,4], but have yet to be detected. A less exotic alternative is normal matter in the form of bodies with masses ranging from that of a large planet to a few $M_\odot$. Such objects, known collectively as massive compact halo objects[5] (MACHOs) might be brown dwarfs or 'Jupiters' (bodies too small to produce their own energy by fusion), neutron stars, old white dwarfs, or black holes. Paczynski[6] suggested that MACHOs might act as gravitational microlenses, occasionally causing the apparent brightness of distant background stars temporarily to increase. We are conducting a microlensing experiment to determine whether the dark matter halo of our galaxy is made up of MACHOs. Here we report a candidate for a microlensing event, detected by monitoring the light curves of 1.8 million stars in the Large Magellanic Cloud for one year. The light curve shows no variation for most of the year of data taking, and an upward excursion lasting over 1 month, with a maximum increase of ≈ 2 mag. The most probable lens mass, inferred from the duration of the event, is $\sim 0.1\,M_\odot$.

The MACHO Project[7,8] uses the gravitational microlens signature to search for evidence of MACHOs in the Galactic halo, which is thought to be at least three times more massive than the visible disk[2]. (Two other groups are attempting a similar search[9,10].) If most of our Galaxy's dark matter resides in MACHOs, the 'optical depth' for microlensing towards the Large Magellanic Cloud (LMC) is about 5×10^{-7} (independent of the mass function of MACHOs), so that at any given time about one star in two million will be microlensed with an amplification factor A > 1.34 (ref. 5). Our survey takes advantage of the transverse motion of MACHOs relative to the line-of-sight from the observer to a background star. This motion causes a transient, time-symmetric and achromatic brightening that is quite unlike any known variable star phenomena, with a characteristic timescale $\hat{t} = 2r_E/v_\perp$ where r_E is the Einstein ring radius and $v_\perp$ is the MACHO velocity transverse to the line-of-sight. For typical halo models, the time with A $> 1.34 \sim 100\sqrt{M_{macho}/M_\odot}$ days[5] (where $M_\odot$ is the mass of the sun). The amplification can be large, but these events are extremely rare; for this reason our survey was designed to follow $>$ ten million stars over several years.

The survey employs a dedicated 1.27m telescope at Mount Stromlo. A field-of-view of 0.5 square degrees is achieved by operating at the prime focus. The optics include a dichroic beam-splitter which allows simultaneous imaging in a 'red' beam ($6300 - 7600$Å) and a 'blue' beam ($4500 - 6300$Å). Two large charge coupled device (CCD) cameras[11] are employed at the two foci; each contain a 2×2 mosaic of 2048×2048 pixel Loral CCD imagers. The 15 μm pixel size corresponds to 0.63 arcsec on the sky. The images are read out through a 16 channel system, and written into dual ported memory in the data acquisition computer. Our primary target stars are in the LMC. We also monitor stars in the Galactic bulge and the Small Magellanic Cloud. As of 15 September 1993, over 12000 images have been taken with the system.

The data are reduced with a crowded-field photometry routine known as Sodophot, derived from Dophot[12]. First, one image of each field that was obtained in good seeing is reduced in a manner similar to Dophot to produce a 'template' catalog of star positions and magnitudes. Normally, bright stars are matched with the template and used to determine an analytic point spread function (PSF) and a coordinate transformation. Photometric fitting is then performed on each template star in descending order of brightness, with the PSF for all other stars subtracted from the frame. When a star is found to vary significantly, it and its neighbors undergo a second iteration of fitting. The output consists of magnitudes and errors for the two colors, and six additional useful parameters (such as the χ^2 of the PSF fit and crowding information). These are used to flag questionable measurements that arise from cosmic ray events in the CCDs, bad pixels, and so on.

These photometric data are subjected to an automatic time-series analysis which uses a set of optimal filters to search for microlensing candidates and variable stars (which we have detected in abundance[13]). For each microlensing candidate a light-curve is fitted, and the final selection is done automatically using criteria (for example signal-to-noise, goodness of fit, achromaticity, color) that were established empirically using Monte Carlo addition of fake events into real light-curves.

This analysis has been done on four fields near the center of the LMC, containing 1.8 million stars, with approximately 250 observations for each star. The candidate event reported here occurs in the light-curve of a star at coordinates $\alpha = 05\ 14\ 44.5, \delta = -68\ 48\ 00$ (J. 2000). (A finding

chart is available on request from C. A.). The star has median magnitudes $V \sim 19.6$, $R \sim 19.0$, consistent with a clump giant (metal-rich helium core burning star) in the LMC. These magnitudes are estimated using color transformations from our filters to V and R that have been derived from observations of standard stars.

Our photometry for this star, from July 1992 to July 1993 is shown in Figure 1, and the candidate event is shown on an expanded scale in Figure 2, along with the color light curve. The color changes by < 0.1 mag as the star brightens and fades. A mosaic, showing portions of some of the CCD images used, is shown in Figure 3, with the relevant star at the center. The integrated number of PSF photoelectrons detected above the sky background in the template image is $\approx 10^4$, for a 300 sec exposure. The increase in counts during the peak is highly significant, as is clear from the Figures.

Also shown in Figure 2 is a fit to the theoretical microlensing light-curve (see ref. 6). The four parameters fit are (1) the baseline flux; (2) the maximum amplification $A_{max} = 6.86 \pm 0.11$; (3) the duration $\hat{t} = 33.9 \pm 0.26$ days; (4) the centroid in time 433.55 ± 0.04 days. The quoted errors are formal fit errors. Using the PSF fit uncertainties as determined by the photometry program, the best-fit microlensing curve gives a χ^2 per degree of freedom of 1.6 (for 443 d.o.f.).

A number of features of the candidate event are consistent with gravitational microlensing: the light curve is achromatic within measurement error, and it has the expected symmetrical shape. If this is a genuine microlensing event, the mass of the deflector can be estimated. Since the duration depends upon the lens mass, the relative velocity transverse to the line-of-sight, and the distance to the lens, (none of which are known), the lens mass cannot be uniquely determined from the duration. However, using a model of the mass and velocity distributions of halo dark matter, one can find the relative probability that a MACHO of mass m gave rise to the event. Thus, if this is geniune microlensing, Fig. 9 of Ref. 5 implies the most likely mass is approximately $0.12 M_\odot$, with masses of $0.03 M_\odot$ and $0.5 M_\odot$ being roughly half as likely. However, this method does not properly take into account our detection efficiencies, and should be considered only a rough estimate.

The mass range given above includes brown dwarfs and main sequence stars, raising the possibility of direct observation of the object. Even a star of $0.5 M_\odot$, however, would have $V \sim 24$,

and for many years would be within a small fraction of an arcsecond of the much brighter LMC star.

We emphasize that the observed stellar brightening could be due to some previously unknown source of intrinsic stellar variability. The fit discrepancy near the peak is not yet understood; a more refined analysis of the data is underway. We do not yet have a spectrum of the star. A crucial test of the hypothesis that we are seeing gravitational microlensing by MACHOs in the galactic halo will be the detection of other candidates. So far, we have analysed only $\sim 15\%$ of our first year's frames, and we plan to continue observations until 1996; this will allow us to determine whether or not gravitational microlensing is really the cause. Additional events should show the theoretically expected distribution of maxima, and should be representative of both the color-magnitude diagram and the spatial structure of the LMC. No repeats should be seen in any given star! (While this paper was in preparation, we were informed by J. Rich (personal communication) of another comparable event observed by the collaboration reported in ref. 9; note that the two groups use different definitions of characteristic time.)

If such candidates do result from microlensing we should be able to determine the contribution of MACHOs to the dark matter in the Galactic halo. The results presented here encourage us to believe this will happen.

Figure Captions

Figure 1   The observed light-curve with estimated $\pm 1\sigma$ errors. The upper panel shows A_{blue}, the flux (in linear units) divided by the median observed flux, in the blue passband. The lower panel is the same for the red passband. The smooth curve shows the best-fit theoretical microlensing model, fitted simultaneously to both colors. Time is in days from 1992 Jan 1 00:00 UT.

Figure 2   As in Figure 1, with expanded scale around the event. The curve shows the theoretical microlensing model, fitted simultaneously to both colors. The bottom panel is the color light curve, showing the ratio of red to blue flux, normalized so that the median is unity.

Figure 3   Selected Red CCD frames centered on the microlens candidate, showing observations before, during and after the event.

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