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 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 solar masses. 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, temporarily amplifying the apparent brightness of background stars in nearby galaxies. 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 such 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 candidate lensing event, is ~0.1 solar mass.

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 as massive as 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 $t=2r_{\rm E}/v_{\perp}$ where $r_{\rm E}$ is the Einstein ring radius and $v_{\perp}$ is the MACHO velocity transverse to the line-of-sight. For typical halo models the time $t\sim100\sqrt{M_{\rm macho}/M_{\odot}}$ 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 1.27-m 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 (6,300–7,600 Å) and a 'blue' beam (4,500–6,300 Å). Two large charge-coupled device (CCD) cameras[11] are employed at the two foci; each contain a 2 × 2 mosaic of 2,048 × 2,048 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 12,000 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' catalogue 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 neighbours undergo a second iteration of fitting. The output consists of magnitudes and errors for the two colours, 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, quality of fit, wavelength independence of the light curve and colour of the star) 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 centre 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 h 14 min 44.5 s, $\delta=-68^{\circ}\,48'\,00''$ (J2000). (A finding chart is available on request from C.A.). The star has median magnitudes $V\sim19.6$, $R\sim19.0$, consistent with a clump giant (metal-rich helium core burning star) in the LMC. These magnitudes are estimated using colour 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 Fig. 1, and the candidate event is shown on an expanded scale in Fig. 2, along with the colour light curve. The colour changes by <0.1 mag as it brightens and fades (the candidate 'event'). A mosaic, showing portions of some of the CCD images used, is shown in Fig. 3, with the relevant star at the centre. The integrated number of PSF photoelectrons detected above the sky background in the template image is $\sim10^4$, for a 300 s exposure. The increase in counts during the peak is highly significant, as is clear from the figures. Also shown in Fig. 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 $A_{\rm max}=6.86\pm0.11$, (3) the duration $t=33.9\pm0.26$ d, (4) the centroid in time 433.55 ± 0.04 d. 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.f.).

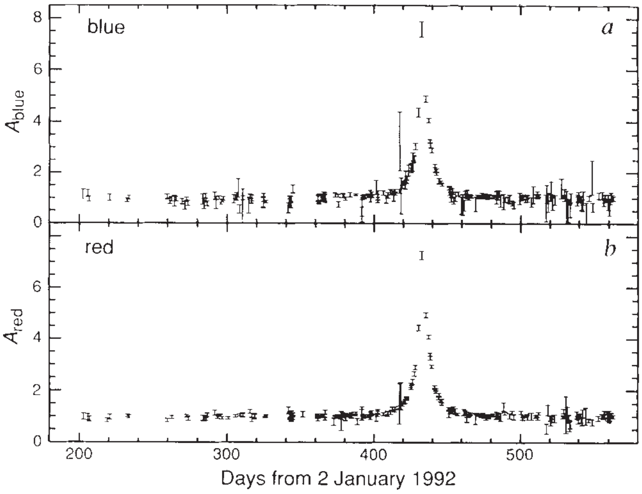

FIG. 1 The observed light curve with estimated $\pm 1\sigma$ errors. *a* Shows A_{blue}, the flux (in linear units) divided by the median observed flux, in the blue passband. *b* Is the same, for the red passband.

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. Because 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. But by 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_{macho} gave rise to the event. Thus, if this is genuine microlensing, Fig. 9 of ref. 5 implies the most likely mass is $\sim 0.12\, M_{\odot}$, 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. Any microlensing star is very unlikely to be a red dwarf of the Galactic stellar halo, because one can show that the optical depth τ_s for microlensing by main sequence stars of the stellar halo is very low. Even if the mass function of the stellar halo rises as steeply as $dN/dM \propto M^{-4}$, as suggested recently[14] (here N is the number of stars per unit stellar mass interval), τ_s is still a few hundred times smaller than the 5×10^{-7} optical depth estimated for MACHO microlensing. The chance of finding such a stellar microlensing event among our 1.8 million stars is therefore very small.

The prospects for direct observation of a lensing object are not favourable. Even a star of $0.5\, M_{\odot}$, for example, 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 under way. 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 ~15% of our first year's frames and we plan to continue observations until 1996; this should allow us

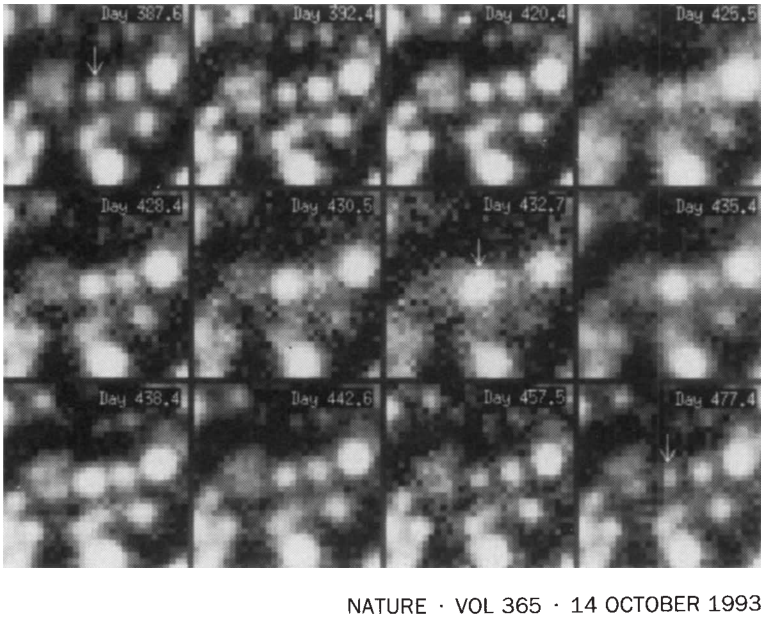

FIG. 3 Selected red CCD frames centred on the microlens candidate, showing observations before, during and after the event. The numbers on each frame indicate the days after 2 January 1992.

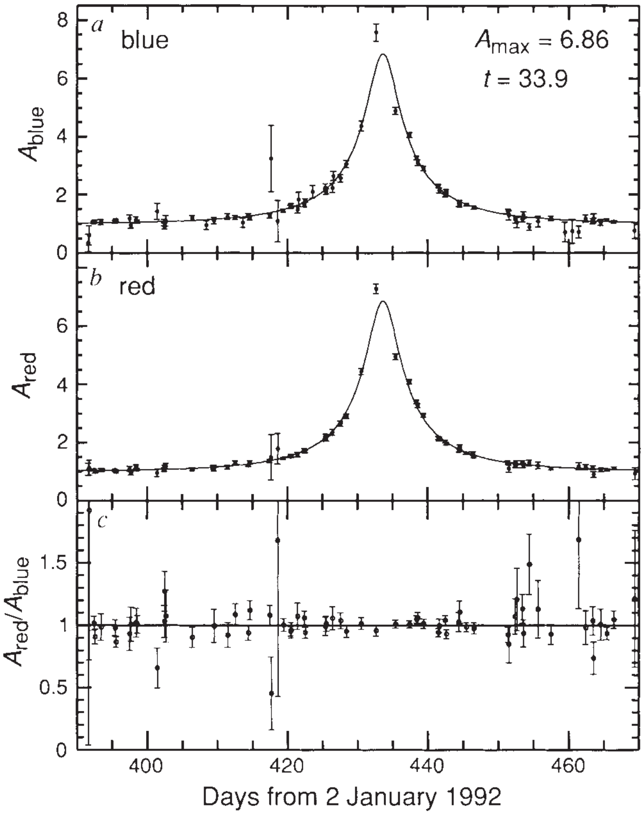

FIG. 2 As in Fig. 1, with an expanded scale around the candidate event. The smooth curve shows the best-fit theoretical microlensing model, fitted simultaneously to both c is the colour light curve, showing the ratio of red to blue flux, normalized so that the median is unity.

to determine if microlensing is really the cause. Additional events should show the theoretical distribution of maxima, and should be representative of both the colour–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 the candidate events reported by the EROS collaboration. 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. ☐

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Evidence for gravitational microlensing by dark objects in the Galactic halo

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THE flat rotation curves of spiral galaxies, including our own, indicate that they are surrounded by unseen haloes of 'dark matter'[1,2]. In the absence of a massive halo, stars and gas in the outer portions of a galaxy would orbit the centre more slowly, just as the outer planets in the Solar System circle the Sun more slowly than the inner ones. So far, however, there has been no direct observational evidence for the dark matter, or its characteristics. Paczyński[3] suggested that dark bodies in the halo of our Galaxy can be detected when they act as gravitational 'microlenses', amplifying the light from stars in nearby galaxies. The duration of such an event depends on the mass, distance and velocity of the dark object. We have been monitoring the brightness of three million stars in the Large Magellanic Cloud for over three years, and here report the detection of two possible microlensing events. The brightening of the stars was symmetrical in time, achromatic and not repeated during the monitoring period. The timescales of the two events are about thirty days and imply that the masses of the lensing objects lie between a few hundredths and one solar mass. The number of events observed is consistent with the number expected if the halo is dominated by objects with masses in this range.

The 'EROS' (Expérience de Recherche d'Objets Sombres) collaboration is searching for microlensing events using the European Southern Observatory at La Silla, Chile[4,5]. We have two complementary programmes. The first uses $5^\circ \times 5^\circ$ Schmidt plates of the Large Magellanic Cloud (LMC) that allow us to monitor about eight million stars with a sampling rate of no more than two measurements per night. This makes the programme primarily sensitive to lens masses in the range $10^{-4}\,M_\odot < M < 1\,M_\odot$ (where $M_\odot$ is the solar mass), corresponding to mean lensing durations in the range $1\,\mathrm{d} < \tau < 100\,\mathrm{d}$. The probability that a given star in the LMC is amplified by more than 0.3 magnitudes at a given time is calculated to be $\sim 0.5 \times 10^{-6}$ (refs 3, 6). For a deflector of mass M the typical timescale for the amplification is $\tau = 70\sqrt{M/M_\odot}$ d. The light curve of such an event should be symmetric in time, achromatic, and the event should not be repeated. Over the period 1990–93, a total of 304 Schmidt plates of the LMC were taken for us at La Silla with red or blue filters. Exposure times were typically