The Astrophysical Journal, 491:L11–L13, 1997 December 10

FIRST DETECTION OF A GRAVITATIONAL MICROLENSING CANDIDATE TOWARD THE SMALL MAGELLANIC CLOUD

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Received 1997 August 20; accepted 1997 October 8; published 1997 November 6

ABSTRACT

We report the first discovery of a gravitational microlensing candidate toward a new population of source stars, the Small Magellanic Cloud (SMC). The candidate event's light curve shows no variation for 3 yr before an upward excursion lasting ∼217 days that peaks around 1997 January 11 at a magnification of ∼2.1. Microlensing events toward the Large Magellanic Cloud and the Galactic bulge have allowed important conclusions to be reached on the stellar and dark matter content of the Milky Way. The SMC gives a new line of sight through the Milky Way and is expected to prove useful in determining the flattening of the Galactic halo.

Subject headings: galaxies: individual (Small Magellanic Cloud) — Galaxy: halo — gravitational lensing

1. INTRODUCTION

Gravitational microlensing has become a new tool for discovering and characterizing populations of dark objects. By nightly monitoring of millions of stars, several groups have detected the rare brightenings that occur when a dark object passes between a source star and the observer (Alcock et al. 1993; Aubourg et al. 1993; Udalski et al. 1993; Alard et al. 1995). These events have led to powerful statements on the dark matter content of the Milky Way (Alcock et al. 1996a, 1997b; Renault et al. 1997), strong limits on the possibility of planetary mass dark matter (Alcock et al. 1996c; Aubourg et al. 1995), as well as important discoveries regarding the distribution of mass toward the Galactic bulge (Alcock et al. 1997a; Udalski et al. 1994). See Paczyński (1996) or Roulet & Mollerach (1997) for a general review, and Beaulieu et al. (1995) and Ansari et al. (1995) for discussion of the interpretation of EROS events. All previous microlensing results were found using source stars either toward the Large Magellanic Cloud (LMC) or the Galactic bulge, although microlensing searches toward M31 have also been undertaken and possible events have been reported (Crotts & Tomaney 1996). In this Letter we announce the first discovery of a microlensing candidate toward a new target galaxy, the Small Magellanic Cloud (SMC). The candidate event's light curve shows no variation for 3 yr before an upward excursion lasting ∼217 days that peaks around 1997 January 11 at a magnification of ∼2.1.

The SMC gives a new line of sight through the Milky Way halo and a new population of source stars. Microlensing toward the SMC is important since a comparison of the microlensing rate toward the SMC with the rate toward the LMC has been predicted to be a powerful way of measuring the flattening of the Milky Way dark halo (Sackett & Gould 1993; Frieman & Scoccimarro 1994; Alcock et al. 1995). Most workers assume that the dark halo is spherical, but there is little observational or theoretical reason to believe this is so. A direct measurement therefore would be very valuable. In addition, new lines of sight allow for discrimination between various theories (Zhao 1997) for the populations responsible for LMC microlensing. A dwarf galaxy or possible stellar stream between us and the LMC is unlikely to also be responsible for microlensing toward the SMC. In addition, since initial microlensing results toward both the LMC and bulge were surprising, the potential for initial surprises from SMC microlensing is large.

2. DATA

The MACHO microlensing survey employs a dedicated telescope on Mount Stromlo, Australia with two simultaneous red and blue passbands and a 0.5 deg^2 field of view. See Alcock et al. (1996a) and references therein for details of the telescope, camera, photometry, database, and analysis systems. We have published results on 22 LMC fields (Alcock et al. 1996a, 1997b, 1996c) containing on the order of 8.5×10^6 stars over a period of 2 yr, and our 4 yr analysis of 30 LMC fields is currently underway. For the SMC we have monitored 21 fields, six with good temporal coverage, for a period of 4 yr. These top six fields in the SMC contain approximately 2.2×10^6 stars. Exposures of 300 s were taken for all LMC and early SMC images, but owing to crowding and distance, they were subsequently increased to 600 s for the SMC. Approximately $\frac{2}{3}$ of the over 4400 observations of the top six SMC fields are 600 s. Altogether, SMC observations span the dates 1993 May 15 to the present, giving an average of 730 observations per field with a mean sampling of about 2–3 days.

For the SMC, photometry over our entire 4 yr data set has

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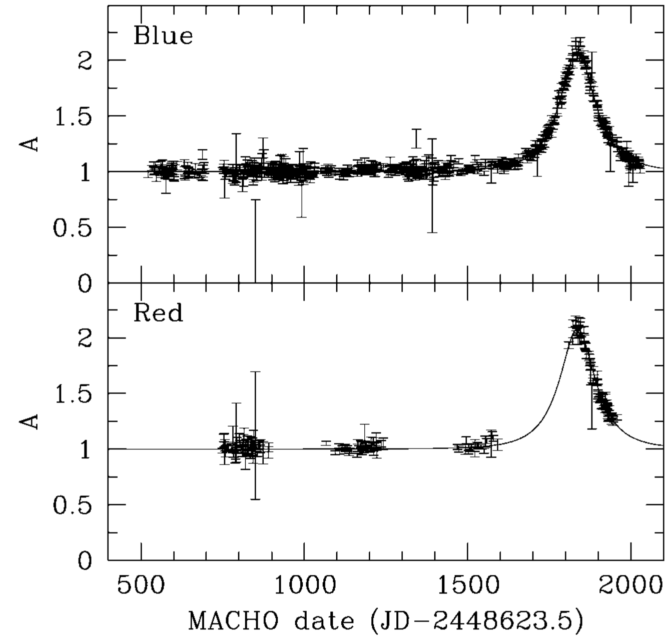

FIG. 1.—Observed light curve for 207.16604.214, with estimated $\pm 1\ \sigma$ errors. The upper panel shows $A_{\rm blue}$, the flux (in linear units) divided by the median observed baseline flux, in the blue passband. The lower panel is the same for the red passband. The smooth curve shows the best-fit theoretical (nonblended) microlensing model, fitted simultaneously to both colors. Some data points are missing from the red light curve owing to a dead area on one CCD.

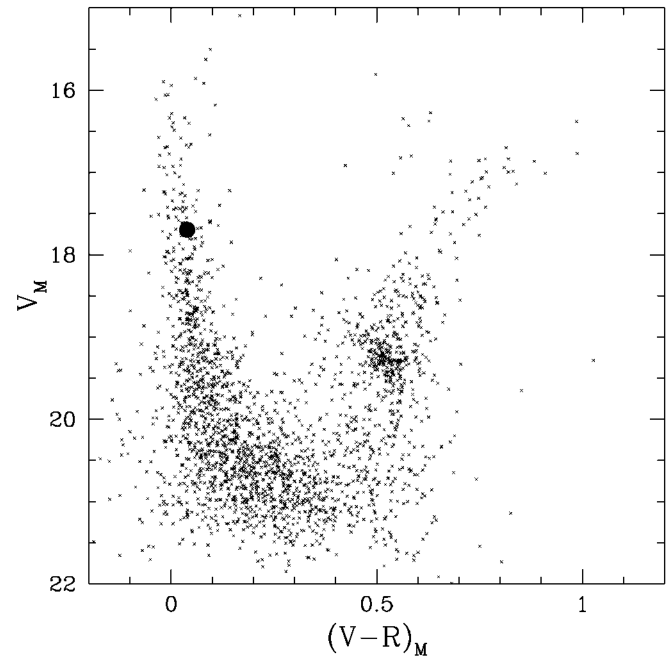

FIG. 2.—Color-magnitude diagram of stars within roughly 5′ of the SMC microlensing candidate. The magnitudes are approximately Kron-Cousins V and R. The candidate is marked as a large dot.

not yet been completed, but after running our alert software on over 2 yr of photometry, possible microlensing candidates, as well as possible supernova and nova candidates, were found. Figure 1 shows the photometric light curve for the best microlensing candidate found by this method. The source star in this event is located at $\alpha = 01^{\rm h}00^{\rm m}05\overset{\rm s}{.}7$, $\delta = -72°15'01''$ (J2000). A finding chart is available from the authors. The star has median magnitudes $V = 17.70$ and $R = 17.66$. A color-magnitude diagram for the area near this star is shown in Figure 2, which indicates that this is an upper main-sequence star.

Also shown in Figure 1 is a fit to the theoretical microlensing light curve (see Paczyński 1986). There are five parameters to the fit: (1 and 2) the baseline fluxes, (3) the maximum magnification $A_{\rm max} = 2.074 \pm 0.005$, (4) the duration (Einstein ring diameter crossing time) $\hat{t} = 216.5 \pm 1.1$ days, and (5) the time of peak magnification $t_0 = 1836.0 \pm 0.3$ days, or roughly 1997 January 11. The $\chi^2_{\rm ml}$ to the fit is 2391 with 857 degrees of freedom. A measure of the signal-to-noise ratio (Alcock et al. 1996a) is given by $\Delta\chi^2/\chi^2_{\rm ml} \equiv (\chi^2_{\rm const} - \chi^2_{\rm ml})/\chi^2_{\rm ml} \approx 30,000$. However, examination of the best seeing images shows that the source star is blended with another SMC star. An image showing the blend is available from the authors. We performed another fit taking into account this possibility, in this case finding a best-fit blend with ~72% of the flux in the lensed primary, giving $A_{\rm max} = 2.5$, $\hat{t} = 247$ days, and an almost identical t_0 and χ^2/dof $= 2.77$. Using a stack of good seeing images and an image obtained from our alert system (Alcock et al. 1996b), we performed independent photometry and find the source likely to be a blended star with 77% of the flux in the lensed primary. Using image differencing techniques (Tomaney & Crotts 1996) to subtract the primary also gives similar results. A blended fit with the blend fraction set to 77% gives $A_{\rm max} = 2.4$, $\hat{t} = 242$ days, and again χ^2/dof $= 2.77$. The source could contain other undetected blended stars, so the above blend fractions are upper limits, implying a duration of $\gtrsim$217–247 days. We note that a centroid shift of a star during lensing can also give information about blending (Alard et al. 1995), but we did not perform this analysis in this case since we can resolve the stars in some images.

Given the flat baseline, high signal-to-noise ratio, the good shape, and the achromaticity, we classify this as an excellent microlensing candidate. However, even taking into account the blend, the source star is more luminous than previous LMC events and is near the region of the color-magnitude diagram susceptible to contamination from "bumper"-type variable stars (Alcock et al. 1996a). Apart from this, it passes the selection criteria used for LMC microlensing in Alcock et al. (1997b), and it also passes selection criteria used for bulge events.

The scatter in the light curve around the fit is larger than the photometry error bars imply, as the fit χ^2/dof of 2.8 indicates. This χ^2/dof is somewhat larger than for most of our LMC microlensing events (Alcock et al. 1997b); however, the SMC is a new target, and we have not yet characterized our photometry as we have for the LMC and bulge. The blending also causes systematic errors in the photometry. Currently, a more refined analysis of the data is underway, including a difference frame analysis that may greatly reduce the problems associated with blending (Tomaney & Crotts 1996).

3. DISCUSSION

A comparison of the SMC and LMC microlensing optical depth is very useful. Almost independent of the dark matter halo model, the ratio $\tau_{\rm LMC}/\tau_{\rm SMC}$ gives a good measurement of the flattening of the halo (Sackett & Gould 1993; Frieman & Scoccimarro 1994; Alcock et al. 1995). The optical depth is the probability that a given star is lensed and can be estimated from $\tau_{\rm est} = (\pi/4E)\Sigma\hat{t}_i/\varepsilon(\hat{t}_i)$, where E is the total exposure in star years, and $\varepsilon(\hat{t}_i)$ is the detection efficiency for event i (Alcock et al. 1996a).

Since we have not yet run our standard analysis to select microlensing events or the Monte Carlo simulation needed to calculate $\varepsilon(\hat{t}_i)$, we cannot yet give a good estimate of $\tau_{\rm SMC}$. For a very rough estimate for this one event alone, we can use $E \sim 2.2 \times 10^6$ stars times the roughly 850 days in this preliminary search and use $\epsilon \sim 0.3$–0.5 from the LMC (Alcock et al. 1997b). Then with the durations quoted above, we find $\tau \sim 1.5 \times 10^{-7}$ to 3×10^{-7}, consistent with that of our reported LMC optical depth (Alcock et al. 1997b). Note that this estimate will change when the search over all the SMC data is completed, when proper values of E and ϵ are calculated, and when proper event selection is performed.

We note that the long duration of this event (217 days) would imply a mass of approximately $\sim 2.5\ M_\odot$ for lenses in a standard dark halo with masses of $1.0\ M_\odot$ and $10.0\ M_\odot$ being roughly half as likely. For a blended fit of $\hat{t} = 247$ days, the corresponding mass would be $3.2\ M_\odot$. However, it is also possible that both the lens and source belong to the SMC. In this case, a wide range of lens masses would be consistent with $\hat{t} = 217$–247 days and internal velocities $v \approx 30$ km s^{-1} for the SMC, depending upon the line-of-sight depth of the SMC. The line-of-sight depth of the SMC is relevant to the interpretation of observed microlensing events and has been studied by several authors (Mathewson, Ford, & Visvanathan 1986; Welch 1985; Welch et al. 1987; Caldwell & Coulson 1986). We conclude from Caldwell & Coulson (1986) and Welch et al. (1987) that the extreme line-of-sight depth at any position in the SMC is unlikely to be greater than 12 kpc and that in field 207 (in the north-central region of the SMC) is unlikely to be greater than 6 kpc and possibly much less. Thus, naively, one does not expect the optical depth from SMC/SMC lensing to be large enough to account for even one such event. A more complete analysis will be presented elsewhere after photometry and analysis of the SMC fields have been completed.

We are grateful for the support given our project by the technical staff at the Mount Stromlo Observatory. Work performed at LLNL is supported by the DOE under contract W-7405-ENG-48. Work performed by the Center for Particle Astrophysics personnel is supported by the NSF through AST 9120005. The work at MSSSO is supported by the Australian Department of Industry, Science, and Technology. K. G. and M. J. L. acknowledge support from DOE, Alfred P. Sloan, and Cottrell Scholar awards. C. S. acknowledges the generous support of the Packard, Seaver, and Sloan Foundations. W. S. is supported by a PPARC Advanced fellowship.

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