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# Resolving the Nature of the LMC Microlensing Event LMC-5

A. J. Drake[1,2,3], K. H. Cook[3] AND S.C. Keller[4]

## ABSTRACT

We present the results from an analysis of Hubble Space Telescope High Resolution Camera data for the Large Magellanic Cloud microlensing event MACHO-LMC-5. By determining the parallax and proper motion of this object we find that the lens is an M dwarf star at a distance of $578^{+65}_{-53}$pc with a proper motion of $21.39 \pm 0.04$ mas/yr. Based on the kinematics and location of this star it more likely to be part of the Galactic thick disk than thin disk population. We confirm that the microlensing event LMC-5 is a jerk-parallax microlensing event.

*Subject headings:* stars: low-mass – Galaxy : halo – dark matter

## 1. Introduction

For over a decade astronomers have been observing the Magellanic Clouds in order to determine the fraction of the dark matter in our Galaxy that may be in the form of Massive Compact Halo Objects (MACHOs). The discovery of a significant number of microlensing events in the first two years of the MACHO project lead to an uncertain initial estimate that approximately half of the halo was composed of MACHOs (Alcock et al. 1997). With 3.7 years of additional data this estimate decreased to $\sim 20\%$ of the halo (Alcock et al. 2000). While it appears these objects make up a significant fraction of the mass in the Galactic halo, little is known about their nature other than that their most probable masses lie in the range of 0.15 and $0.9 M_{\odot}$

In order to obtain the most accurate information which can be gained from a microlensing event, it is useful to accurately determine the flux of the star that was lensed. This is made difficult for sources in crowded fields such as LMC because they are usually blended

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with neighboring stars. In many cases each "object" identified in ground-based observations consists of the blend of a number of stars (Alcock et al. 2000). The exact location of the source star is also poorly known because of blending. To determine the locations of the sources Alcock et al. (2001a, 2001b) analyzed the MACHO project images using Difference Image Analysis (Alcock et al. 1999, 2001a). With these positions they were able to subsequently identify and photometer the microlensing source stars in observations taken with *Hubble Space Telescope* (hereafter HST) Wide Field Planetary Camera 2 (WFPC2).

Among the events discovered by the MACHO project toward the Magellanic clouds was event LMC-5. This event had a high magnification ($\sim$50) and was detected in the light curve of Macho object 6.5845.1091 which is located at $\alpha = 05^{\rm h}16^{\rm m}41\overset{\rm s}{.}1$, $\delta = -70^{\circ}29'18''$ (J2000). Gould, Bachall & Flynn (1997) suggested that the baseline color of this event was not consistent with an LMC source star and they proposed that the anomalous color could be attributed to the source being blended with a M dwarf in the Galactic disk. As the likelihood of finding and M dwarf within the seeing disk is small they proposed an M dwarf could be the lens in the foreground. Alcock et al. (1997) found that the color of the source was in agreement with the colors and magnitudes of LMC stars, but the event was indeed blended with a red object. Most of the LMC microlensing events found by Alcock et al. (1997) were blended to some extent. When the source star in this microlensing event was identified in HST observations it was discovered that there was a faint red star nearby. The probability of finding an unrelated foreground M dwarf near the microlensing source star is $\sim$ 1 in 10000 (Alcock et al. 2001b). With this in mind, it was thought very likely that this object was the lens.

The LMC-5 event shows the clear sign of microlensing parallax. In these events, the motion of the Earth during the event changes the shape of the microlensing light curve from the classical Paczyński form (Gould 1992, Alcock et al. 1995). The presence of parallax enables limits to be placed on the mass and location of the microlens. The parallax fit for this event yielded a lens motion direction that was consistent with the red star having been the lens. However, the solution also suggested that the lens was likely to be a sub-stellar object of 0.036$M_\odot$ ($\leq$ 0.097$M_\odot$ at 3-$\sigma$ significance) at a distance of $\sim$ 200pc. Alcock et al. (2001b) derived a separate distance estimate for the lens using the objects color and spectral type. First a spectrum of the lens-source combination was obtained and it was found that the prospective lens was an M4V or M5V type star. The V-I color of the object was determined from HST WFPC2 photometry. This color was converted into an absolute magnitude using the $M_V$ vs $V - I$ relation of Reid (1991) for M dwarfs. The distance was then obtained from the observed and absolute magnitudes while the errors in distance were estimated from the dispersion in M dwarf magnitudes $V - I \sim 3$. The result was that the object was at $650 \pm 190$pc, in stark contrast to the microlensing parallax solution.

If the red object is indeed the lens, a measurement of the parallax should confirm the distance inferred from the color of the object in the HST images. In addition, a measurement of the magnitude and direction of the proper motion should agree with the initial estimate which assumed the red object was the lens, and that the relative separations of the two objects represented its proper motion.

To resolve the nature of the candidate lens we undertook a program of observations with HST's Advanced Camera System High Resolution Camera (hereafter ACS and HRC, respectively). In the meantime, a new solution to the LMC-5 puzzle was proposed by Gould (2004) based on the recent work of Smith, Mao and Paczyński (2003). By exploring the phase space of "vector microlens parallax" in a geocentric reference frame, Gould (2004) discovered a second solution to the microlensing parallax which varied from the original solution of Alcock et al. (2001b) by less than 0.1 in fit $\chi^2$.

The microlens vector parallax of this second solution differs from that of the first solution by the so called "jerk parallax", a vector whose direction lies perpendicular to the direction of the Earth's acceleration and whose magnitude (for LMC events) is about $(4/3)(\mathrm{yr}/2\pi \mathrm{t_e}) \sim 2.4$. Events exhibiting these so-called "jerk-parallax degeneracies" are expected to be rare for microlensing toward the LMC, unless the lens resides in the Galactic disk. In the case of the LMC-5 microlensing event, Gould (2004)'s jerk-parallax solution is in agreement with the lens distance and direction estimated from the HST photometry.

The solution of Gould (2004) does not rule out the possibility that the initial solution to the microlensing fit was the correct one, since both are equally good fits to the lensing light curve. However, when this solution is considered in combination with the other evidence from the HST data it is much more likely that the lens is a sub-stellar object not detected in the HST data. In this paper we will show with certainty that Gould (2004)'s solution is the correct one.

## 2. Observations

We obtained images with the HST's HRC in July 2002 and January 2003. The observations were taken approximately six months apart to maximize the parallactic offset of the lens relative to proper motion vector. Each set of observations consists of 6 images of the source - lens field, allowing us to perform robust cosmic ray rejection and to determine very accurate centroids for each object. The observations taken in 2002 used the F606W and F814W filters, while the observations in 2003 were taken in the F606W filter alone. The duration of each of the exposures was 400 seconds.

## 3. Analysis

The HRC images contain significant distortion in the form of a skew due to the off-axis location of the ACS. To determine the distortion corrected location of the stars in the HRC images, we followed the analysis of Anderson and King (2004). In this process, the standard flat fielded (flt) HRC images simply were fed into Anderson and King's "img2xym" task. This program finds stars within the images and fits each with an effective Point Spread Function (ePSF) which is based on an instrumental PSF modified by the sub-pixel offset of each star's center. The ePSF varies between observational filters so the correct starting PSF must be chosen. The centroid location and flux of each star is determined in the fitting process. However, because of the large amount of image distortion the instrumental magnitudes and locations require correction to an undistorted system where the offset and the changing effective pixel area are corrected. The "img2xym" task also performs these steps to provide corrected stellar locations and instrumental magnitudes. The RMS scatter after the corrections of Anderson and King (2004) is $< 0.01$ pixels, or about 0.25mas, for the brightest stars in each image.

For each image, we determined the offset between the source star and the assumed lens. We combined the results for each photometric band separately, and estimated the uncertainties in these positions based on the scatter in their locations. In addition, we combined these locations with the lower resolution results obtained by Alcock et al. (2001b) from analysis of HST WFPC2 observations taken in June 1999. It was not possible to estimate the parallax with the prior HST data since there was only one known location (the WFPC2 point) and one assumed position at the source star during the microlensing event.

In Table 1 we present a summary of the observations used in this analysis. We fitted the proper motion and parallax of the object using the times and locations of the measurements. This fit places the M dwarf at an offset of $(\Delta X, \Delta Y) = (2.2 \pm 9.9, -1.6 \pm 7.8)$ mas at the time of the microlensing event. The reduced $\chi^2$ value of this fit is $< 0.1$. This suggests that the errors in the locations are over estimated, and the the real uncertainty in this offset if much smaller. The main contributor to the uncertainty in the location is the error in the HST WFPC2 location. However, this result makes it quite certain that the red object is indeed the lens. The source star itself is not stationary but moving with the proper motion of the LMC which is $(\mu_{\alpha\mathrm{LMC}}, \mu_{\delta\mathrm{LMC}}) = (1.68, 0.34)$ mas/yr (van der Marel et al. 2002). However, in the case of microlensing events we are only interested in the motion of the lens relative to the source.

With the lens identified, an additional constraint for determining the proper motion and trigonometric parallax of the lens was derived from the fact that we know that the source star and the lens must be collinear in our line-of-sight at the time of the microlensing

event peak amplification. We fitted the locations again to determine the proper motion and parallax of the lens with the inclusion of this additional point. We find the proper motion of the lens relative to the source to be $(\mu_{\alpha \mathrm{SL}}, \mu_{\delta \mathrm{SL}}) = (17.56 \pm 0.04, -12.22 \pm 0.02\ )$ mas/yr. The position angle of the proper motion vector is $\theta = 124.8°$. This in exellent agreement with the direction of Gould (2004)'s solution of 123.9°. The direction of proper motion given by Alcock et al. (2001b), $\theta_{sky} = -91.6°$ (ecliptic coordinates), appears to be incorrect as this transforms to 138.4° (Gould 2004) rather than 124° as derived from the the HST WFPC data.

We find the parallax of the lens to be $\pi_{\mathrm{L}} = 1.73 \pm 0.18$ mas. Therefore, the lens lies at a distance of $578^{+65}_{-53}$ pc. This result is in agreement with the previous photometric estimate of Alcock et al. (2001b) (650 pc). The fact that we have been able to measure a $\sim 2$ mas parallax to $\sim$10% uncertainty is a good demonstration of the astrometric accuracy that can be achieved with the HST HRC instrument.

In Figure 1 we present the fit to the motion of the LMC-5 lens corrected for the source star motion. The solid line shows the fit to the HST data including the source star location as a point, while the dashed line shows the proper motion and parallax that is expected with the lens distance of 200pc as determined from the original microlensing parallax fit. The fit shown in this figure is slightly more constrained than it appears since the times of the measurements are an important the fitting process. The F606W and F814W HRC points taken in July 2002 should lie very close to each other. However, as the figure shows they are significanty offset. We have checked for systematic errors in the transformations of Anderson and King (2004) by matching a large number of stars between the F606W and F814W frames. The coordinates of these stars matched within the centroid uncertainties while the lens appeared to be slightly offset between bands. However, the current level of uncertainty is too large to tell whether the offset is real or due to an unquantified localized distortion.

If we assume the lens undergoes average Galactic foreground reddening for the LMC of E(B-V) = 0.06 (Oestreicher, Gochermann, Schmidt-Kaler 1995), we find $M_V = 13.68$, consistent with an M5 dwarf star. Our results are in agreement with the spectra and $M_V$ presented by Alcock et al. (2001b). It is very difficult to observationally rule out the possibility that a $0.036\mathrm{M}_{\odot}$ object at 200pc as the lens since the object could be fainter than 30th magnitude in V band (Baraffe et al. 1998). This mass lies below the limits where models are accurate. However, K band observations may be more promising. The fact that we know that foreground M dwarfs are extremely rare in fields toward the LMC (Alcock et al. 2001b) suggests this object is very likely the lens. From our initial parallax and proper motion fit we known that the object was within a few milli-arcseconds of the source at the time of the

lensing event. Our results agree with the new jerk-parallax solution discovered by Gould (2004). Therefore, there is almost no doubt that the M dwarf we have observed is the indeed the lens.

For the lens we find the space velocity components (U,V,W) to be (43.2,-55.7,29.0) km.s$^{-1}$ corrected to the Local Standard of Rest. These values are much higher than those presented by Alcock et al. (2001b) as they assumed a distance of 200pc and are quite high for thin disk M dwarfs. However, the displacement from the Galactic plane ($\sim$300pc) and the velocity are consistent with both thin and thick disk stars. We have simulated the stellar population of disk and halo stars toward the LMC field following the method of Vallenari, Bertelli, and Schmidtobreick (2000). Using a common range of disk parameters (scale height, scale length, etc.). We find that the lens is slightly more likely to be a thick disk star ($\sim 50 \pm 30\%$) than a thin disk one. Clearly the likelihood is strongly dependent on adopted parameters for the Galactic components. The kinematics are also in good agreement with the thick disk kinematics derived by Chiba and Beers (2000).

## 4. Conclusions

We have analyzed HRC data for LMC microlensing event LMC-5 and we find that the lens in this microlensing event is an M dwarf star. Based on our analysis we can confirm that the jerk-parallax solution to the microlensing light curve discovered by Gould (2004) is correct. The kinematics of this star suggest that it is most likely a part of the Galactic thick disk population rather than part of the dark halo. This is the first time that any microlens has been identified with such certainty. However, this discovery does not affect the current estimates of the mass fraction of the Galactic dark halo in the form of MACHOs, since some microlensing events due to foreground disk stars are expected in all LMC microlensing models.

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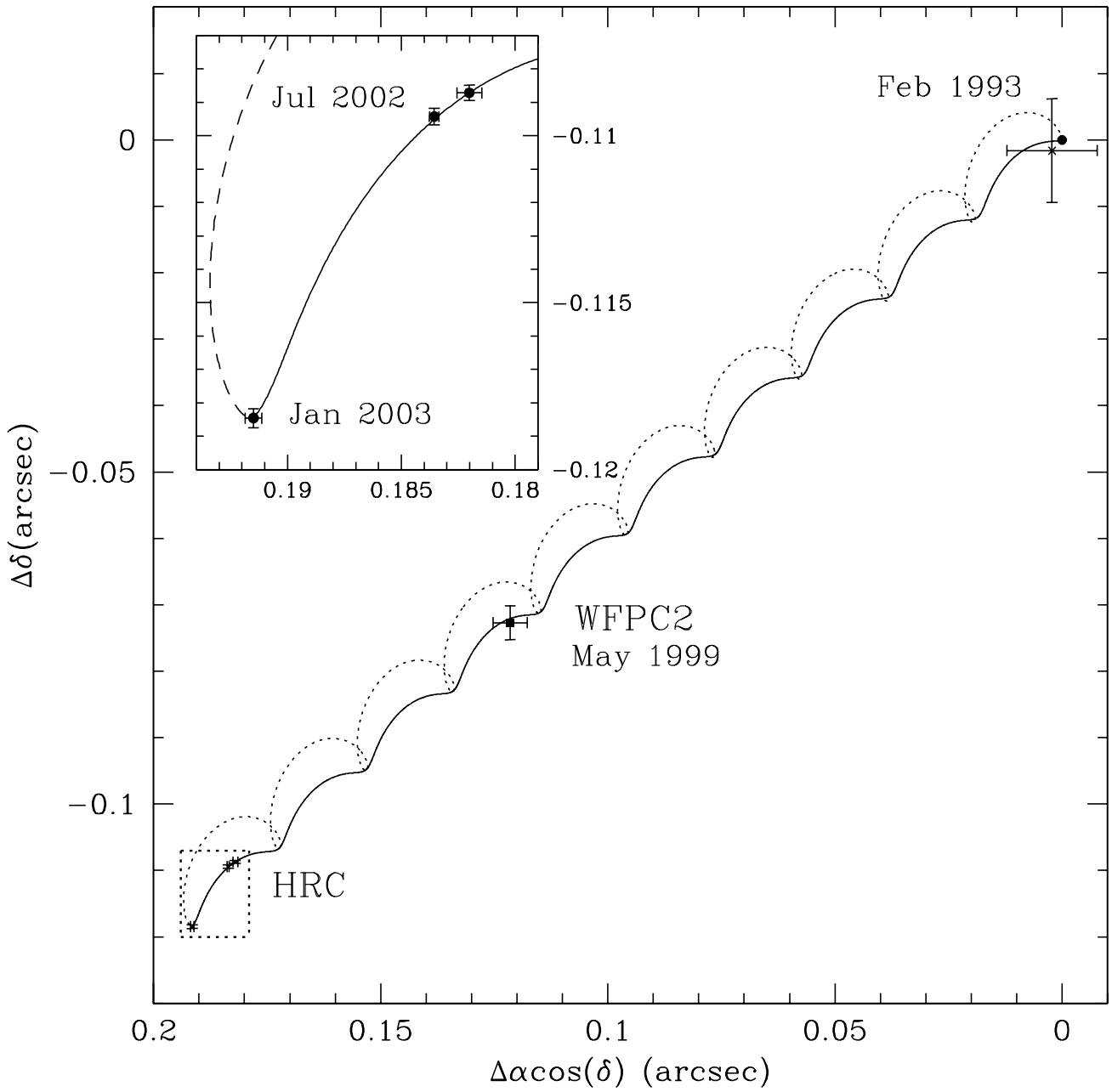


Fig. 1.— Motion of the microlens relative to the position MACHO source star 6.5845.1091 at the time of the microlensing peak magnification. The insert presents an expanded view of dotted region where locations were determined with the HRC instrument. The dot at (0,0) shows the location of the source star and the large errors bars near (0,0) shows the position of the object at the time of the microlensing event determined from the initial parallax and proper motion fit. See the text for further details.

Table 1. Astrometric data for LMC-5.

| Observations | $\Delta\alpha$ $''$ | $\Delta\delta$ $''$ | Time days |
|---|---|---|---|
| WFPC2 (F555W & F814W) | $0.1110 \pm 0.0038$ | $-0.0748 \pm 0.0026$ | 2288.16 |
| ACS HRC (F606W) | $0.16618 \pm 0.00055$ | $-0.11263 \pm 0.00023$ | 3442.55 |
| ACS HRC (F814W) | $0.16772 \pm 0.00021$ | $-0.11192 \pm 0.00024$ | 3442.64 |
| ACS HRC (F606W) | $0.17484 \pm 0.00037$ | $-0.12183 \pm 0.00028$ | 3621.52 |

Note. — Col. (1), instrument and filters used in observations. Cols. (2) & (3), relative offsets between source and lens in right ascension (great-circle) and declination, respectively. Col. (4), observation time relative to peak time of lensing event (JD=2449023.9).

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