Spitzer Space Telescope Observations of the Aftermath of Microlensing Event MACHO-LMC-5

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ABSTRACT

We have carried out photometry of the microlensing event MACHO-LMC-5 with Spitzer’s IRAC ten years after the magnification of the LMC source star was recorded. This event is unique in the annals of gravitational microlensing: the lensing star itself has been observed using HST (once with WFPC2 and twice with ACS/HRC). Since the separation between the source and lens at the epoch of the Spitzer observations was $\sim 0.24''$, the two stars cannot be resolved in the Spitzer images. However, the IRAC photometry clearly establishes that the lens is a M5 dwarf star from its infrared excess, which in turn yields a mass of $\sim 0.2M_\odot$. This demonstrates the potential of Spitzer to detect the lenses in other gravitational microlensing events.

1. Introduction

It is over a decade since gravitational microlensing was first clearly detected (Alcock et al. 1993), and there has been enormous progress since then (Alcock et al. 2000a; Afonso et al. 2003). Over 1,000 events have been recorded, most towards the Galactic bulge; the total towards the Large and Small Magellanic Clouds is $\sim 25$ (Alcock et al. 2000a; Afonso et al. 2003). The Magellanic Cloud events are of great importance because they probe the contribution of MACHOs (Massive Compact Halo Objects) to the dark matter in the halo of the Milky Way (Paczynski 1986). The measured microlensing event rate towards the Large Magellanic Cloud exceeds that expected from previously known stellar populations (Alcock et al. 2000a). The interpretation of this excess of events remains controversial, with four potential explanations dominating the discussion:

1. The lenses belong to the halo of the Milky Way. In this case the MACHO Project concluded that objects of mass $\sim 0.5M_\odot$ comprise about 20% of the dark halo (Alcock et al. 2000a).

2. The lenses belong to some previously undetected population that belongs to the LMC (Sahu 1994; see also Zhao 1998). Models of the LMC do not generally produce sufficient microlensing event rates to account for the data (Gould 1995, 1998; Alves & Nelson 2000; Gyuk, Dalal, & Griest 2000; van der Marel et al. 2002). Tidal debris that is not in dynamical equilibrium with the LMC has also been discussed (Weinberg & Nikolaev 2001; Zhao et al. 2003). Efforts to detect various models for these putative populations have been unsuccessful (Alcock et al. 2001a; Alves 2004).
3. The lenses belong to some previously undetected dwarf galaxy that lies between us and the LMC (Zaritsky & Lin 1997; Zaritsky et al. 1999). This is now considered very improbable (Gould 1999).

4. The lenses belong to a previously undetected component of the disk of the Milky Way (Alcock et al. 2000a; note that the known components cannot account for the microlensing event rate), or to an undetected disk-like structure (Gates & Gyuk 2001). This suggestion is less popular than (1) and (2), but does receive some support in the story of event MACHO-LMC-5.

The truth, of course, may be a combination of these, and there is great interest in elucidating the true nature of these events (Gates, Gyuk, & Turner 1996; Kerins & Evans 1999; Green & Jedamzik 2002; Jetzer, Mancini, & Scarpetta 2002). It is in this context that the special importance of the MACHO-LMC-5 is manifest. During a 76 day period in 1993, the brightness of MACHO-LMC-5 increased by a factor of 47 due to the passage of a foreground object (the lens) close to our line of sight to the source. The lens and source are now separated by $\sim 0.24''$. MACHO-LMC-5 is the only event in history for which both the source star and the lens have been detected (Alcock et al. 2001b). In the original report on the HST WFPC2 image showing the lens, the observed source-lens relative proper motion was strikingly consistent with the motion determined by the fit to the microlensing event itself. The mass of and distance to the lens were estimated from the fit to the microlensing data, and separately from spectra and the photometric data; these two independent estimates appeared to differ significantly. Gould (2004) suggested that a phenomenon called “jerk parallax” was responsible for this discrepancy. Microlensing parallax is the asymmetry in a magnification event induced by the acceleration of the Earth around the Sun. “Jerk” is the time derivative of this acceleration. Gould’s interpretation was confirmed by Drake, Cook & Keller 2004 using new images of the system taken with HST’s ACS/HRC. They concluded that the lens is very probably a dwarf M5 star at a distance of $\approx 600$pc from the sun.

We have begun a program of deep photometry of lensed LMC stars using the Spitzer Space Telescope. We start with MACHO-LMC-5 because of its great importance, because it should be readily detected in Spitzer’s IRAC bands, and because we plan to use these observations as a model for further analysis of other LMC events. In most cases the lens cannot be resolved from the source, even with HST resolution (Alcock et al. 2001a), but a cool stellar lens in a Galactic disk population may show up as an infrared excess (von Hippel et al. 2003). MACHO-LMC-5 is indeed detected, as we report here. Observations of additional LMC microlensing source stars will be presented in a later paper.

We present data on the MACHO-LMC-5 system in which we have detected the lens with Spitzer at wavelengths out to the $8\mu$m band. We establish photometrically that the lens is
a late M star and also demonstrate the utility of Spitzer observations for characterizing the lensing population. In this paper, we will use the phrase “MACHO-LMC-5” to refer to the combination of the target star and the lens, which cannot be spatially separated by Spitzer\(^1\). “LMC-5 lens” refers to the foreground cold object which produced the microlensing, and “LMC-5 source” to the background LMC star which was magnified.

### 2. Observations

MACHO-LMC-5 was observed with the IRAC near/mid-infrared camera on board Spitzer at UT 2003 December 05. IRAC is a four-channel camera consisting of two pairs of 256 × 256 pixel InSb and Si:As IBC detectors to provide simultaneous images at 3.6, 4.5, 5.8, and 8\(\mu\)m. Two adjacent 5.12 × 5.12 arcmin fields of view are viewed by the four channels in pairs (3.6 and 5.8\(\mu\)m; 4.5 and 8\(\mu\)m) \(^2\). The fields of view were centered on 05h16m40s, -70d29m04s (J2000), which is the position of the LMC-5 event. The target area was imaged using a 12-position Reuleaux triangle dither pattern, at approximately 7 to 8 arcseconds per step, with two 30-second frametime exposures made at each dither position. The net result was 720 s of integration on MACHO-LMC-5 in each IRAC band. Additional observations of MACHO-LMC-5 with the MIPS 24\(\mu\)m band are planned for April 2004.

### 3. Data Reduction and Analysis

The individual frames were processed (to remove cosmic rays and artifacts, primarily a streak due to a bright star just to the east of MACHO-LMC-5; the streak was particularly noticeable at 5.8\(\mu\)m and 8\(\mu\)m, where it interfered with our ability to obtain accurate photometry of MACHO-LMC-5), and co-added to produce the images used for astrometry and photometry. The co-added frames have pixel size 0.6”, half the native pixel scale for IRAC.

Figure 1 shows the entire processed image of this field taken in the 4.5\(\mu\)m band. Figure 2 shows six images, each of the same small region including MACHO-LMC-5: (a) the MACHO Project R-band image, (b) I-band with the HST WFPC2 imager, (c) 3.6\(\mu\)m IRAC image, (d) 4.5\(\mu\)m IRAC image, (e) 5.8\(\mu\)m IRAC image, and (f) 8\(\mu\)m IRAC image. The lens and source are clearly resolved in the HST image, but unresolved in the MACHO and IRAC

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\(^{1}\)The full-width at half-maximum of the PSF is \(\sim 1.8\).  
\(^{2}\)IRAC 3.6 and 4.5\(\mu\)m bands have effective wavelengths similar to the widely used L and M filters respectively (Fazio et al. 2004 this issue).
images. Note that the complex of stars around MACHO-LMC-5 seen in the MACHO image is clearly seen in the Spitzer images, particularly at 3.6 and 4.5\(\mu\)m.

The MACHO-LMC-5 complex is the Eastern member of a pair of objects separated by \(\sim 2"\) roughly in the E-W direction. The Western member of the pair is the star shown to the right of MACHO-LMC-5 in the HST image. This star is considerably brighter than the MACHO-LMC-5 complex in both \(R\)-band and \(I\)-band, but in the IRAC images MACHO-LMC-5 is about as bright as this star. This can be attributed to the fact that the lens, which is substantially cooler than the source star, dominates the flux at longer wavelengths.

**Astrometry.** In order to identify MACHO-LMC-5 in our IRAC data, we identified the region of interest using the lower resolution MACHO-\(R\)-band image and then made use of HST \(I\)-band data on MACHO-LMC-5 (Figure 2(b)). The HST data does not suffer from confusion, and all the relevant stars are well isolated. In addition, we know which the lens, the source, and the field star are in the HST image. We ran DAOPHOT on both the IRAC and HST fields to get astrometric centroids for the stars. For each data set (IRAC and HST) we then computed both the distance between MACHO-LMC-5 and a bright reference star present in both the HST and the IRAC images, and the distance between this bright star and the field star. The ratio of distances determined for the two separate images agreed to within a few percent, allowing us to identify MACHO-LMC-5 and its closest neighbor with confidence in the IRAC images.

**Photometry.** Photometry was done on the cleaned, co-added images using DAOPHOT. In these mosaics the individual frames in the dithers were coadded in sky coordinates with the SSC mosaicer software using 0.6" pixels, half the native pixel scale for IRAC. The PSF radius was set to 6" (DAOPHOT keyword \texttt{psfrad} = 10 pixels), and the fit radius was set to 3.6" (DAOPHOT keyword \texttt{fitrad} = 6 pixels). Aperture corrections were performed for these source apertures (3 pixels in the native IRAC pixel scale). Magnitude zero points were determined using data provided by the Spitzer Science Center. The Jy to 0 mag conversions used were 277.5, 179.5, 116.6 and 63.1 for the 3.6, 4.5, 5.8 & 8\(\mu\)m bands respectively. Table 1 shows all the photometric data available for MACHO-LMC-5 as well as photometry for two late-type dwarfs used for comparison (Bessell 1991, Leggett 1992, Patten et al. 2004).

4. Discussion and Conclusions

The images and photometry in Table 1 clearly show that MACHO-LMC-5 exhibits substantial infrared excess. This was already apparent in the separate \(V - I\) colors for the source and the lens from the HST data. Given the faintness of the LMC-5 source star as seen
in the HST images and the likelihood that it is an early G-type star, based on its \( V - I \) color (Alcock et al. 2001b), we estimate that the source star will contribute less than 10% of the flux of the combined MACHO-LMC-5 within the IRAC bandpasses. Therefore, within the errors on the photometry, MACHO-LMC-5 has mid-infrared colors consistent with a late-M dwarf or possibly an early-L dwarf (Patten et al. 2004).

The jerk parallax fit (Drake, Cook, & Keller 2004) yields a distance of \( 578 \pm 65 \) pc, equivalent to a distance modulus of \( 8.81 \pm 0.2 \) for the lens. The corresponding absolute magnitudes of the lens in IRAC bands are given in Table 2. Table 2 also lists absolute magnitudes from IRAC photometry of GJ1156 (M5.0V) and LHS3003 (M7.0V), both of which have Hipparcos trigonometric parallaxes (Patten et al. 2004). Clearly the M5.0 V star is the best match for MACHO-LMC-5. Because the absolute magnitudes for low-mass stars fall off rapidly for later spectral types, this eliminates the consideration of L dwarfs as possibilities for the color match. Likewise, the lens can be no earlier spectral type than M4.5 V. Therefore, the IRAC photometry shows that the lens is an M5 dwarf and thus has a mass of \( \sim 0.2M_\odot \) (Henry & McCarthy 1993, Delfosse et al. 2000). The characterization of this spectacular event is now complete.

The lens in MACHO-LMC-5 belongs to the disk of the Milky Way. The distance and space motions are consistent with the thick disk, as noted by Drake, Cook & Keller (2004). Since a fraction of all microlensing candidates are expected to come from the disk, we cannot say anything conclusive about the nature of the microlenses in general with just this one event. Thus, while MACHO-LMC-5 might be an example of the fourth possibility listed in the Introduction, on its own it does not suggest the existence of a previously unknown component. However, the clear detection of the infrared excess in MACHO-LMC-5 demonstrates the capability of Spitzer to detect cool, low mass stellar lenses as candidates for the other microlensing events if this is indeed the case. Previous searches for infrared excesses have yielded only upper limits (von Hippel et al. 2003). The sensitivity and mid-infrared spectral coverage of Spitzer will allow much more sensitive searches for the lenses corresponding to other microlensing events in the future.

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Fig. 1.— A full image of the MACHO LMC-5 field taken with the IRAC 4.5 µm band. The boxed region highlights the MACHO-LMC-5 (left) & field star (right) pair.
Fig. 2.— (a) Aftermath of MACHO-LMC-5 image in $R$-band (Alcock et al. 2001). (b) High resolution image of LMC-5 in $I$ band taken by HST/WFPC2 six years after the lensing (Alcock et al. 2001). The lens is the object in the far left, and is $\sim 3$ PC pixels (0.134") away from the source which is dimmer than the lens in $I$-band. The bright object to the right is a field star, and is 1.90 arcsec from the source. (c), (d), (e) and (f) show LMC-5 in IRAC's 3.6, 4.5, 5.8 and 8 $\mu$m bands. Note that the field star is brighter than LMC-5 in $R$ and $I$ bands but comparable or dimmer in all IRAC bands, indicating that IR flux is dominated by the cooler lens which is moving away from source at roughly 24 mas per year. (a), (c), (d), (e) and (f) have the same plate scale. In all images, North is up and East is to the left.
### Table 1. The photometry

| Star             | V     | (V − I)$_c$† | 3.6µm | 4.5µm | 5.8µm | 8µm | V − 3.6µm |
|------------------|-------|---------------|-------|-------|-------|------|-----------|
| LMC-5 source     | 21.02 ± 0.06 | 0.68 ± 0.09  | -     | -     | -     | -    | -         |
| LMC-5 lens       | 22.67 ± 0.10 | 3.18 ± 0.11  | -     | -     | -     | -    | -         |
| MACHO-LMC-5      | 20.80 ± 0.12 | 1.72 ± 0.14  | 16.33 ± 0.03  | 16.47 ± 0.04 | 16.70 ± 0.15 | 16.83 ± 0.29 | 4.47 ± 0.12 |
| GJ1156           | 13.80 | 3.45          | 7.18 ± 0.02  | 7.17 ± 0.01  | 7.13 ± 0.03  | 7.07 ± 0.01  | 6.61 ± 0.02  |
| LHS3003          | 17.05 | 4.52          | 8.42 ± 0.03  | 8.50 ± 0.01  | 8.42 ± 0.01  | 8.33 ± 0.01  | 8.63 ± 0.03  |

† the c refers to the Cousins system.

¶ all error estimates quoted are for relative photometric errors. The absolute calibration of IRAC is believed to be accurate to 10% at this time.

### Table 2. Absolute Magnitudes

| Star             | $M_{3.6\mu m}$ | $M_{4.5\mu m}$ | $M_{5.8\mu m}$ | $M_{8\mu m}$ |
|------------------|---------------|---------------|---------------|-----------|
| GJ1156 (M5.0V)   | 8.11 ± 0.10   | 8.09 ± 0.10   | 8.05 ± 0.10   | 7.99 ± 0.10   |
| LHS3003 (M7.0V)  | 9.48 ± 0.10   | 9.56 ± 0.10   | 9.48 ± 0.10   | 9.39 ± 0.10   |
| MACHO-LMC-5      | 7.52 ± 0.23   | 7.66 ± 0.23   | 7.89 ± 0.27   | 8.02 ± 0.37   |
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