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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* Infrared Array Camera (IRAC) 10 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 the *Hubble Space Telescope* (once with WFPC2 and twice with ACS/HRC). Since the separation between the source and lens at the epoch of the *Spitzer* observations was $\sim 0\overset{''}{.}24$, the two stars cannot be resolved in the *Spitzer* images. However, the IRAC photometry clearly establishes that the lens is an M5 dwarf star from its infrared excess, which in turn yields a mass of $\sim 0.2\ M_\odot$. This demonstrates the potential of *Spitzer* to detect the lenses in other gravitational microlensing events.

Subject headings: gravitational lensing — infrared: stars — Magellanic Clouds

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 2000; Afonso et al. 2003). Over 1000 events have been recorded, most toward the Galactic bulge; the total toward the Large and Small Magellanic Clouds is ∼25 (Alcock et al. 2000; 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 (Paczyński 1986). The measured microlensing event rate toward the Large Magellanic Cloud exceeds that expected from previously known stellar populations (Alcock et al. 2000). 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 $\sim 0.5\ M_\odot$ comprise about 20% of the dark halo (Alcock et al. 2000).
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 et al. 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. 2000; note that the *known* components cannot account for the microlensing event rate) or to an undetected disklike structure (Gates & Gyuk 2001). This suggestion is less popular than explanations 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 et al. 1996; Kerins & Evans 1999; Green & Jedamzik 2002; Jetzer et al. 2002). It is in this context that the special importance of MACHO-LMC-5 is manifest. During a 76 day period in 1993, the brightness of MACHO-LMC-5 increased by a factor of 47 as a result of 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 $\sim 0\overset{''}{.}24$. 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 *Hubble Space Telescope* (*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 et al. (2004) using new images of the system taken with *HST* ACS/HRC. They concluded that the lens is very probably a dwarf M5 star at a distance of ≈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* Infrared Array Camera (IRAC) bands, and because we plan to use these observations

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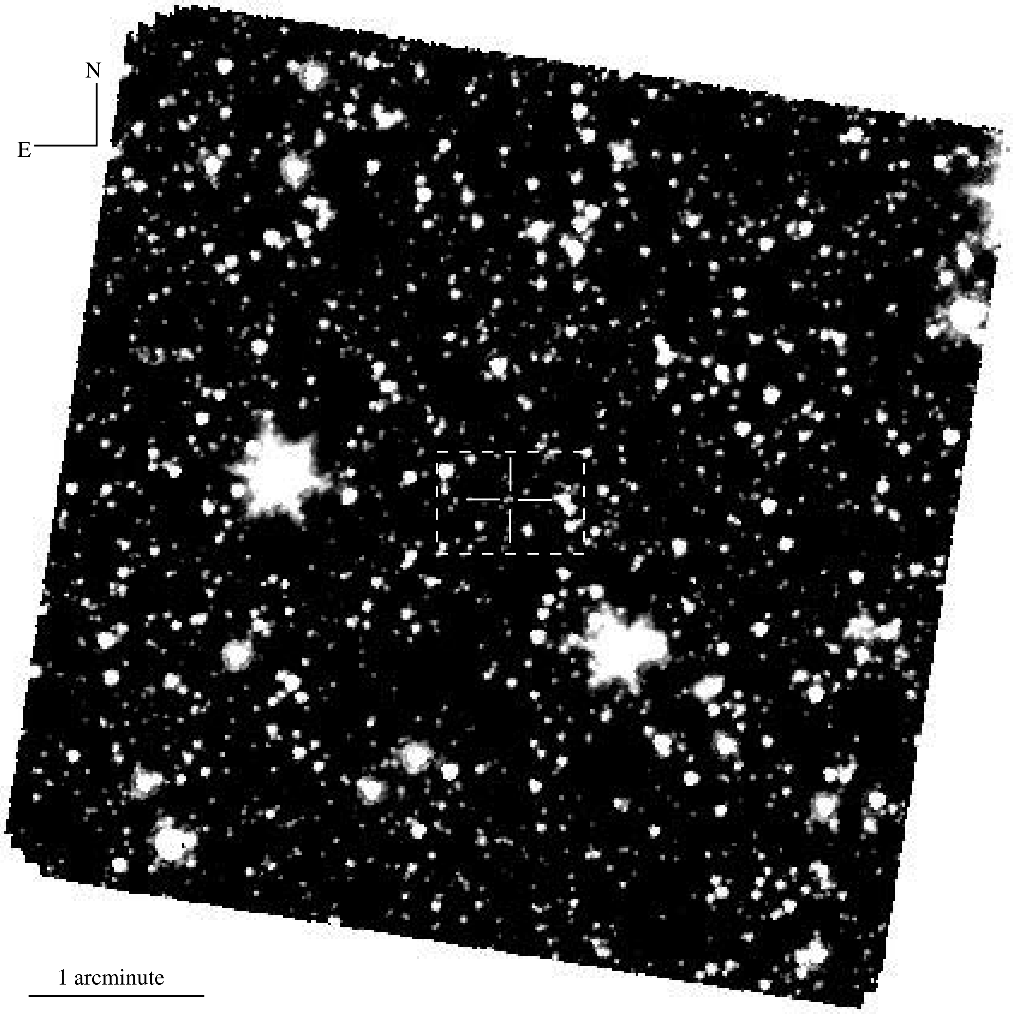

FIG. 1.—Full image of the MACHO LMC-5 field taken with the IRAC 4.5 μm band. The boxed region highlights the MACHO-LMC-5 (*left*) and field star (*right*) pair.

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 μm 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 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*.[4] "LMC-5 lens" refers to the foreground cold object that produced the microlensing, and "LMC-5 source" to the background LMC star that was magnified.

2. OBSERVATIONS

MACHO-LMC-5 was observed with the IRAC near/mid-infrared camera on board *Spitzer* at UT 2003 December 5. 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 μm. Two adjacent $5'.12 \times 5'.12$ fields of view are viewed by the four channels in pairs (3.6 and 5.8 μm; 4.5 and 8 μm).[5] The fields of view were centered on $05^h16^m40^s$, $-70°29'04''$ (J2000.0), which is the position of the LMC-5 event. The target area was imaged using a 12 position Reuleaux triangle dither pattern, at approximately $7''$–$8''$ per step, with two 30 s 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 μm band are planned for 2004 April.

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 and 8 μm, 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.

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[4] The FWHM of the PSF is $\sim 1''.8$.

[5] IRAC 3.6 and 4.5 μm bands have effective wavelengths similar to the widely used L and M filters, respectively (Fazio et al. 2004).

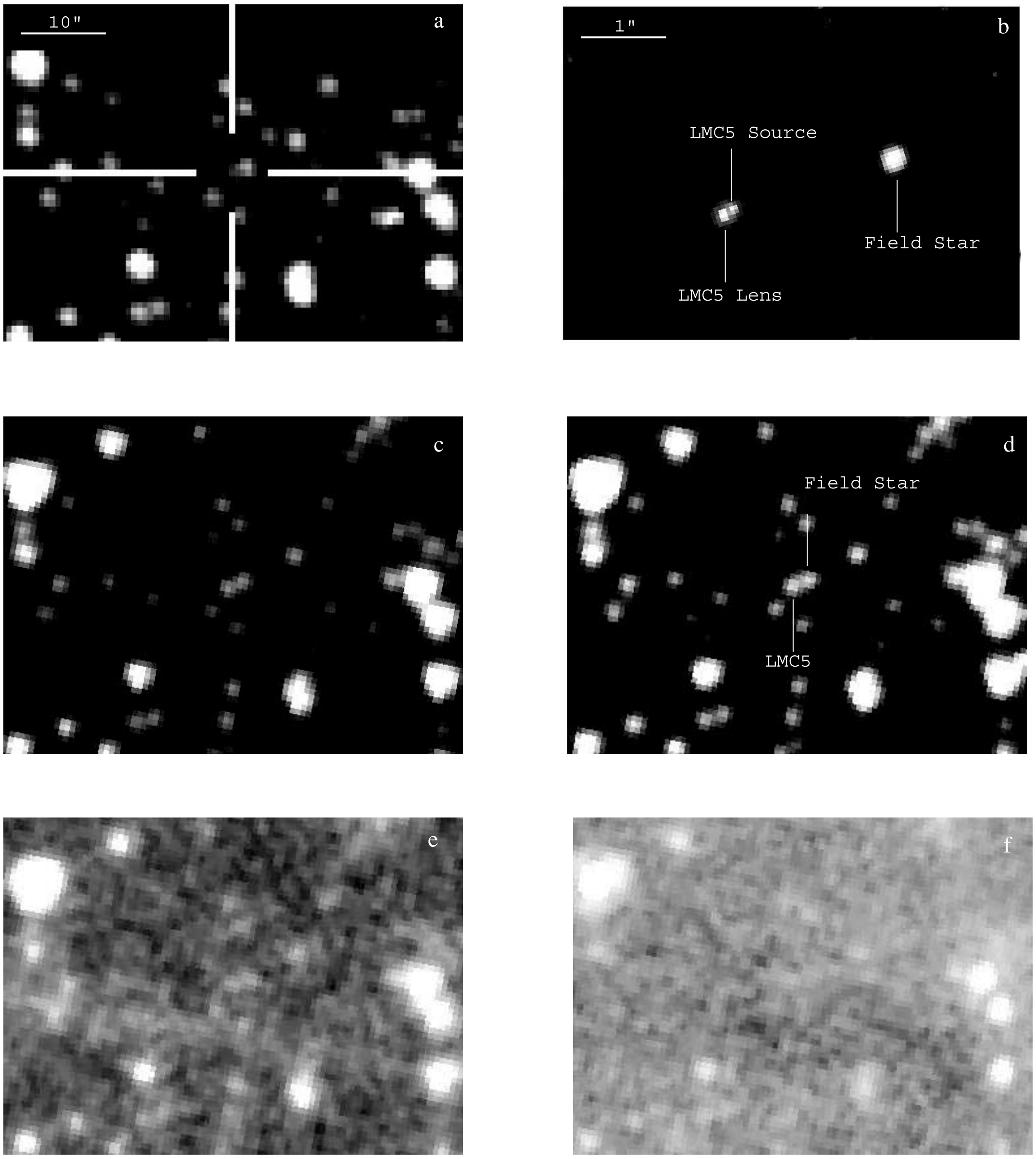

FIG. 2.—(*a*) Aftermath of MACHO-LMC-5 image in *R* band (Alcock et al. 2001a). (*b*) High-resolution image of LMC-5 in *I* band taken by *HST* WFPC2 6 yr after the lensing (Alcock et al. 2001b). The lens is the object in the far left, and is ~3 PC pixels ($0\farcs134$) away from the source which is dimmer than the lens in *I*-band. The bright object to the right is a field star, and is $1\farcs90$ from the source. (*c*), (*d*), (*e*), and (*f*) LMC-5 in IRAC 3.6, 4.5, 5.8, and 8 μm 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 the 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

PHOTOMETRY

Star	V	$(V-I)_C$[a]	[3.6]	[4.5]	[5.8]	[8]	$V-[3.6]$
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[b]	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
LHS 3003	17.05	4.52	8.42 ± 0.03	8.50 ± 0.01	8.42 ± 0.01	8.33 ± 0.01	8.63 ± 0.03

[a] Subscript "C" refers to the Cousins system.

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

Figure 1 shows the entire processed image of this field taken in the 4.5 μm 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 μm IRAC image, (*d*) 4.5 μm IRAC image, (*e*) 5.8 μm IRAC image, and (*f*) 8 μm IRAC image. The lens and source are clearly resolved in the *HST* image, but unresolved in the MACHO and IRAC 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 μm.

The MACHO-LMC-5 complex is the eastern member of a pair of objects separated by $\sim 2''$ roughly in the east-west 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 (Fig. 2*b*). The *HST* data do not suffer from confusion, and all the relevant stars are well isolated. In addition, we know which of 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 co-added in sky coordinates with the *Spitzer* Science Center mosaicker software using $0\overset{''}{.}6$ pixels, half the native pixel scale for IRAC. The point-spread function (PSF) radius was set to $6''$ (DAOPHOT keyword *psfrad* = 10 pixels), and the fit radius was set to $3\overset{''}{.}6$ (DAOPHOT keyword *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 janksy to 0 mag conversions used were 277.5, 179.5, 116.6, and 63.1 for the 3.6, 4.5, 5.8, and 8 μm 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; B. M. Patten et al. 2004, in preparation).

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 (B. M. Patten et al. 2004, in preparation).

TABLE 2

Absolute Magnitudes

Star	$M_{3.6\ \mu\rm m}$	$M_{4.5\ \mu\rm m}$	$M_{5.8\ \mu\rm m}$	$M_{8\ \mu\rm m}$
GJ1156 (M5.0 V)..........	8.11 ± 0.10	8.09 ± 0.10	8.05 ± 0.10	7.99 ± 0.10
LHS 3003 (M7.0 V).....	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

The jerk parallax fit (Drake et al. 2004) yields a distance of 578 ± 65 pc, equivalent to a distance modulus of 8.81 ± 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 GJ 1156 (M5.0 V) and LHS 3003 (M7.0 V), both of which have *Hipparcos* trigonometric parallaxes (B. M. Patten et al. 2004, in preparation). 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 $\sim 0.2\ M_\odot$ (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 et al. (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 § 1, *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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