PHOTOMETRIC CONFIRMATION OF MACHO LARGE MAGELLANIC CLOUD MICROLENSING EVENTS

DAVID P. BENNETT, ANDREW C. BECKER, AND AUSTIN TOMANEY

Received 2005 January 6; accepted 2005 May 6

ABSTRACT

We present previously unpublished photometry of three Large Magellanic Cloud (LMC) microlensing events and show that the new photometry confirms the microlensing interpretation of these events. These events were discovered by the MACHO Project alert system and were also recovered by the analysis of the 5.7 yr MACHO data set. This new photometry provides a substantial increase in the signal-to-noise ratio over the previously published photometry, and in all three cases, the gravitational microlensing interpretation of these events is strengthened. The new data consist of MACHO–Global Microlensing Alert Network (GMAN) follow-up images from the CTIO 0.9 m telescope plus difference imaging photometry of the original MACHO data from the 1.3 m Great Melbourne telescope at Mount Stromlo. We also combine microlensing light-curve fitting with photometry from high-resolution HST images of the source stars to provide further confirmation of these events and to show that the microlensing interpretation of event MACHO LMC-23 is questionable. Finally, we compare our results with the analysis of Belokurov et al., who have attempted to classify candidate microlensing events with a neural network method, and we find that their results are contradicted by the new data and more powerful light-curve fitting analysis for each of the four events considered in this paper. The failure of the Belokurov et al. method is likely to be due to their use of a set of insensitive statistics to feed their neural networks.

Subject headings: gravitational lensing — Magellanic Clouds

Online material: color figures

1. INTRODUCTION

The decade of the 1990s saw the development of gravitational microlensing as a new method to detect objects in the planet–stellar mass range through their gravitational effect on light rays from background stars (Alcock et al. 1993; Aubourg et al. 1993; Udalski et al. 1993). Applications of this method include such diverse topics as the search for baryonic dark matter in the Milky Way halo (Alcock et al. 1997, 2000c; Lasserre et al. 2000; Afonso et al. 2003a), the discovery of planets orbiting distant stars (Bond et al. 2004), limb-darkening measurements of distant stars (Albrow et al. 1999), and obtaining high signal-to-noise ratio spectra of distant stars that would otherwise be possible only with future extremely large telescopes (Lennon et al. 1996; Minniti et al. 1998).

The original proposal for this method was the suggestion by Paczynski (1986) to use microlensing to determine whether the Milky Way’s dark halo is made up of brown dwarfs or Jupiters. (Dark matter objects that can be detected via microlensing are often referred to as massive compact halo objects or MACHOs.) The MACHO and EROS (Expe´ rience de Recherche d’Objets Sombres) groups have completed the microlensing survey proposed by Paczynski (1986), and their main result is the conclusion that the Milky Way’s dark halo is not dominated by objects with masses in the planet-stellar mass range (Alcock et al. 1997, 1998, 2000c, 2001a; Lasserre et al. 2000; Afonso et al. 2003a). Objects in the entire mass range $10^{-7}$–$30\; M_{\odot}$ are excluded from dominating the Milky Way’s dark halo, with upper limits extending down to <5% of the dark halo mass for substellar mass objects. However, the MACHO Project (Alcock et al. 2000c) has found a microlensing signal above the expected background due to lensing by known stellar populations in the Milky Way and the Large Magellanic Cloud (LMC). This signal has a microlensing optical depth equivalent to a dark halo with a MACHO fraction of about 20%, although the total mass could be somewhat smaller if the MACHOs have a distribution that resembles a spheroid or a very thick disk rather than the dark halo (Gates & Gyuk 2001). Some of the first results from M31 microlensing observations appear to confirm this result (Uglesich et al. 2004; Calchi Novati et al. 2005). The timescale of the LMC microlensing events indicates a typical mass of $\sim0.5\; M_{\odot}$, so the most plausible lens objects are white dwarfs, because main-sequence stars of this mass would be much too bright to have previously escaped detection. However, there are a number of potential problems with the white dwarf explanation of this LMC microlensing excess (Torres et al. 2002; Flynn et al. 2003; Brook et al. 2003; García-Berro et al. 2004; Spagna et al. 2004). On the other hand, many of the constraints are evaded if most of the halo white dwarfs have helium atmospheres. It might also be possible to explain the MACHO results with a population dominated by lower mass objects (Rahvar 2005).

The leading alternative explanation for the LMC microlensing excess is that the lens objects are ordinary stars associated with the LMC (Sahu 1994). However, standard models of the LMC predict that MACHO should have detected only 2–4 events from known stellar populations (Wu 1994; Alcock et al. 2000c), and there is a simple dynamical explanation for the small LMC self-lensing optical depth (Gould 1995b). On the other hand, the LMC is not an isolated galaxy and may have had significant dynamical disturbances from the Milky Way (Weinberg 2000; Evans & Kerins 2000), but current LMC models that include these effects still cannot account for the observed microlensing events (Gyuk et al. 2000; Alves 2004; Mancini et al. 2004; Nikolaev et al. 2004) because most of the events do not occur in the regions of the highest predicted LMC self-lensing rate.

The other logical possibility is that the background of microlensing events due to faint stars in the local Galactic disk could have been underestimated, but the lens stars for such events should be readily observed in both high-resolution and IR observations,
as event MACHO LMC-5 has demonstrated (Alcock et al. 2001e; Drake et al. 2004; Gould et al. 2004; Nguyen et al. 2004). In fact, most candidate Milky Way disk events are readily identifiable through their anomalous unmagnified colors in the MACHO data, and, of the other published microlensing candidates, only MACHO LMC-20 appears consistent with lensing by a low-mass disk star. Thus, this possibility appears to be less likely than that of halo or LMC lenses.

Of course, all of this assumes that the MACHO LMC microlensing results are correct. The EROS collaboration has also monitored the LMC for microlensing events but has detected fewer events than MACHO and has reported an upper limit on the microlensing optical depth that is only barely consistent with the MACHO detection (Lasserre et al. 2000). A similar near-discrepancy holds for microlensing toward the Galactic bulge, where MACHO also measured a higher microlensing optical depth (Popowski et al. 2005) than EROS (Afonso et al. 2003b).

In this case, the MACHO result is clearly favored, as it is more consistent with separate measurements by the OGLE (Optical Gravitational Lensing Experiment; Udalski et al. 1994) and MOA (Microlensing Observations in Astrophysics; Sumi et al. 2003) groups, as well as a completely independent measurement by MACHO (Alcock et al. 2000b).

1.1. Event Selection by Neural Networks

The difficulty with interpreting the LMC results combined with the near-discrepancy between the MACHO and EROS results has led Belokurov et al. (2003, 2004; hereafter BEL) to attempt to develop an independent microlensing event selection method for the MACHO data set. In an attempt to improve on the MACHO event selection method, BEL have introduced a method using neural networks instead of the series of simple cuts on statistics used by MACHO. This method seemed promising because neural networks should be able to find a set of event selection cuts that are more efficient at identifying microlensing events than can be easily obtained by more traditional trial-and-error methods. However, a major drawback of neural networks is their “black box” nature: it is not obvious exactly why the neural network might make its event classification decisions. Thus, a neural network could mysteriously fail to identify real microlensing events if there was some subtle difference between the real data and the example events used in the training set for the neural network, and it would be difficult to find such an error. This is the reason that neural networks were not used in the MACHO analysis, and it appears to have led BEL and Evans & Belokurov (2005) to overinterpret their results.

In fact, the specific neural network implementation of BEL has a number of serious flaws. Ideally, one would simply feed the raw time series photometry and error estimates into the neural network and let the neural network sort out how to find microlensing events. With hundreds or thousands of input values, such a neural network would be far too slow to be practical. A practical neural network implementation can be obtained if we reduce the raw light-curve data to a much smaller number of statistics that can be calculated from the raw data. The choice of these statistics is, of course, critical to the success of the neural network classification method, and this is where the method of BEL appears to fail. BEL select a set of statistics that are based on auto- and cross-correlation functions of the light-curve data, with the time series treated as if they were sampled uniformly in time (which they certainly are not). The BEL statistics appear to ignore the measurement errors and to ignore much of the time history information, so it would be somewhat surprising if it could do as well as the MACHO selection method.

Finally, Griest & Thomas (2005) have identified a serious logical flaw in the argument of Evans & Belokurov (2005), who claim that the LMC microlensing optical depth must be lower than the MACHO value. The BEL analysis cannot seriously be considered a method to select microlensing events from a complete data set of millions of light curves because its false alarm rate is $10^4$, which is much higher than the microlensing rate for any plausible Galactic model. Thus, BEL use their method in the only way that they can: they apply it to events that have already passed the MACHO selection criteria. Thus, there is no chance that they could detect events that MACHO missed, so their detection efficiency is necessarily lower, contrary to the claim of Evans & Belokurov (2005). As we see in this paper, the BEL method fails to confirm three events that are almost certainly microlensing events, while “confirming” one microlensing candidate that is almost certainly a variable star. Thus, it seems clear that the current version of the BEL analysis does not help to identify actual microlensing events.

1.2. Paper Organization

This paper is organized as follows. Section 2 describes the data sets used for our analysis and the photometry codes used to convert the images into photometric measurements. Section 3 describes our method for light-curve fitting and our comparison with Hubble Space Telescope (HST) photometry of the candidate microlensed source stars. The detailed modeling of the four individual events presented in this paper are presented in §§ 3.1–3.4. A detailed comparison of the results of BEL’s analysis with our results and other additional data is presented in § 4, and in § 5 we discuss the implications of our results for the interpretation of the microlensing results toward the LMC.

2. DATA AND PHOTOMETRY

2.1. MACHO Data

The events presented in this paper were all identified as microlensing candidates in Alcock et al. (2000c) on the basis of photometry with the standard MACHO SoDoPHOT photometry routine. The SoDoPHOT photometry presented in this paper is essentially identical to that presented in Alcock et al. (2000c). A subset of the MACHO images for these events were also reduced with the DIFIMPHOT difference imaging photometry package (Tomaney & Crotts 1996). In very crowded star fields, the difference imaging method is usually more accurate than the profile-fitting method employed by SoDoPHOT (Alcock et al. 1999a, 2000b; Woźniak et al. 2001). Also, the SoDoPHOT and DIFIMPHOT photometry codes are likely to produce different systematic errors, so a comparison of SoDoPHOT and DIFIMPHOT photometry of the same images can reveal data points that might have been affected by these systematic errors.

2.2. Microlensing Alerts and CTIO Follow-up Data

Event MACHO LMC-4 was the first LMC microlensing event discovered and announced in progress, and this occurred on 1994 October 14. It was discovered while staffing arrangements for MACHO GMAN service observing on the CTIO 0.9 m telescope were still being finalized, and as a consequence, it was not possible to take CTIO data through the peak of the event. Because of this problem with the CTIO data, extra observations were

4 Cerro Tololo Inter-American Observatory, National Optical Astronomy Observatory, operated by the Association of Universities for Research in Astronomy (AURA), Inc., under cooperative agreement with the National Science Foundation (NSF).
scheduled with the MACHO survey telescope (the 1.3 m Great Melbourne telescope at Mount Stromlo) until observations from CTIO could resume. The CTIO data set for this consists of a single observation before the light-curve peak, taken shortly after the event was discovered, and 155 observations taken after the light-curve peak, including 10 baseline observations taken more than a year after the peak. These CTIO data were reduced with the ALLFRAME package (Stetson 1994), and 0.5% was added in quadrature to the ALLFRAME error estimates to account for low-level systematic errors such as flat-fielding errors. (For the MACHO SoDoPHOT photometry, 1.4% is added in quadrature to the SoDoPHOT output errors as described in Alcock et al. [2000c].) Of these 156 measurements, 134 pass our data quality cuts (Alcock et al. 1996b) and are included in this analysis. This is in addition to 730 MACHO red-band and 728 MACHO blue-band photometric measurements from SoDoPHOT that pass our data quality cuts, as well as 85 MACHO red-band and 78 MACHO blue-band images reduced with DIFIMPHOT. The images reduced with DIFIMPHOT were chosen to cover the region of the microlensing magnification, as well as a bit of the baseline.

Microlensing event MACHO LMC-13 was detected and announced on 1996 February 11, near peak magnification, as MACHO 96-LMC-1. Additional observations were immediately requested from the CTIO 0.9 m telescope, and 376 CTIO R-band images were eventually obtained, including 145 baseline measurements taken more than 180 days after the light-curve peak. Of these CTIO measurements, 332 pass our data quality cuts. The data from the MACHO survey include 1074 MACHO red-band measurements and 1176 MACHO blue-band measurements reduced with SoDoPHOT, as well as 84 measurements covering the magnified part of the light curve in each MACHO band reduced with DIFIMPHOT. In addition, there were 47 R-band and 64 V-band measurements from the University of Toronto Southern Observatory (UTSO) 0.6 m telescope. These are included in our fits, but they have only limited time coverage and have larger error bars than the CTIO measurements, so they are not included in our figure. These data were reduced in the same way as the CTIO and LMC-4 data.

The final event in our sample is MACHO LMC-15, which was detected and announced on 1997 January 15 as MACHO 97-LMC-1, well before peak magnification. Additional observations were again immediately requested from the CTIO 0.9 m telescope, and 74 CTIO R-band images were obtained, including 26 baseline measurements taken more than 180 days after the light-curve peak. Of these CTIO observations, 60 pass our data quality cuts. The MACHO survey data set consists of 475 MACHO red-band and 586 MACHO blue-band SoDoPHOT measurements, as well as 47 MACHO red-band and 49 MACHO blue-band DIFIMPHOT measurements. The DIFIMPHOT data cover the magnified portion of the light curve along with the baseline immediately before and after the event.

Important constraints on our analysis of the light-curve data come from the high-resolution HST Wide Field Planetary Camera 2 (WFPC2) images of the microlensed source stars after the microlensing events were over. The reduction of the HST data and the identification of the microlensed source stars are discussed in Alcock et al. (2001c) and Nelson et al. (2005).

3. TESTING THE MICROLENSING HYPOTHESIS WITH HST-CONSTRAINED LIGHT-CURVE FITTING

Unlike many types of stellar variability, it is possible to calculate theoretical microlensing light curves with an accuracy that is much better than observational errors, and this makes light-curve fitting an extremely powerful method for testing the hypothesis that a candidate microlensing event was indeed caused by microlensing. The light curve–fitting method is extremely effective in discriminating against the largest background to microlensing events in the LMC, Type Ia supernovae, as demonstrated in Alcock et al. (2000c). This success is due to the fact that there exist accurate models for Type Ia supernova light curves. The situation is different for Type II supernovae, which do not have an accurate light-curve model. The MACHO Project (Alcock et al. 2000c) was also able to exclude its Type II supernova background by performing fits to Type Ia supernova light-curve models, but this method was only convincing because these same events also had detectable galaxy hosts visible in the MACHO images or in other ground-based images with slightly higher resolution. (Since Type II supernovae occur with young host stars and are usually fainter than Type Ia supernovae, they generally have much brighter host galaxies.) After the removal of the supernovae, the confirmation of microlens candidates becomes a bit more difficult because little is known about the extremely rare types of variable stars that might mimic microlensing events. Thus, we are limited to testing the microlensing model rather than comparing it against another model. This task is complicated by the fact that the photometric errors are mildly non-Gaussian, although the MACHO and GMAN data have managed to remove most of the photometry outliers with cuts on a number of data quality flags. One model parameter that is particularly sensitive to systematic photometry errors is the baseline brightness of the source star. In the crowded fields observed by microlensing surveys, it is quite common for the source star to be blended with other stars within the same seeing disk. Thus, the source star brightness is usually used as a fit parameter, but there is a near-degeneracy in light-curve shapes that can make this parameter difficult to determine from a fit.

Another complication is the fact that ~10% of microlensing events are “exotic” events that do not follow the standard Paczyński light curve. In some cases, such as caustic-crossing binary lens events, the exotic features are so unique to lensing that there can be no ambiguity in the interpretation of the event, such as a caustic-crossing binary lens event like MACHO LMC-9 (Bennett et al. 1996). However, in other cases, such as MACHO LMC-22 (Alcock et al. 2000c), non-microlensing variability can be fitted with an exotic lens model. In view of these considerations, we adopt the following series of steps in order to test the microlensing hypothesis for candidate microlensing events toward the LMC.

1. We fitted each event with a light curve constraining the MACHO blue-band source star brightness to match the V magnitude from the HST observations. (The transformation from the MACHO blue band to the standard Cousins V-band is only weakly dependent on the MACHO red-band magnitude; Alcock et al. 1999b.) The best unconstrained fit should not have a fit \( \chi^2 \) that is significantly lower than the constrained fit unless the source star itself is blended with the lens star.
2. The \( \chi^2/\text{dof} \) (degrees of freedom) values for the fit should be consistent with expectations for real microlensing events. Of particular interest are the \( \chi^2/\text{dof} \) values for the follow-up CTIO and DIFIMPHOT data points and the \( \chi^2/\text{dof} \) values in the light curve peak region (defined as the region where the best-fit magnification is \( A > 1.1 \)). Comparison of the different photometry data sets can indicate if an apparent deviation may be due to systematic photometry errors.
3. If a standard Paczyński model is not a good fit to the data, is there an exotic model that gives a good fit with plausible parameters? If so, are the number of candidates that must be fitted with exotic models consistent with expectations?

4. The fitted MACHO red-band baseline magnitude for the source star is converted to the standard Cousins $R$ band and compared to the $HST$ $R$-band magnitude of the source star. If it does not match, is it consistent with a blending model?

When making a goodness-of-fit judgment, it is important to keep in mind that the photometry errors are non-Gaussian, so Gaussian probabilities do not apply. Figure 1 shows the distribution of fitted $\chi^2$/d.o.f values for a set of Monte Carlo events from the LMC efficiency analysis (Alcock et al. 2001d; black histogram), as well as the observed distribution for Galactic bulge microlensing events found by the MACHO alert system presented in Table 3 are the sum of the individual $\Delta \chi^2$ values for the CTIO data plus the larger of the SoDoPHOT or the DIFIMPHOT $\Delta \chi^2$ values.

3.1. Event MACHO LMC-4

The full MACHO LMC-4 light curve is shown in Figure 2, and Figure 3 shows a light curve close up. The solid line in each plot is the best-fit standard Paczyński light curve, while the fit parameters and $\chi^2$ values are given in Tables 1 and 2. The fit $\chi^2$ decreases by only 0.16 with 1 additional degree of freedom if the $HST$ constraint on the baseline brightness in the MACHO

| Event     | $f_{MB}$ | $f_{MB}$ | $f_{CTIO}$ | $V_M \equiv V_{HST}$ | $R_M$ | $R_{HST}$ | $t_0$ (MJD) | $u_0$ | $t_E$ (days) | $\chi^2$/d.o.f |
|-----------|----------|----------|------------|-----------------------|-------|-----------|-------------|------|--------------|----------------|
| LMC-4     | 0.384(7) | 0.335    | 0.598(16)  | 21.33(3)              | 21.15(6) | 21.09(3) | 1022.86(6) | 0.147(2) | 39.5(7)      | 1.418          |
| LMC-13    | 0.662(2) | 0.564    | 0.77(2)    | 21.76(3)              | 21.38(3) | 21.38(3) | 1511.2(2)  | 0.320(7) | 66.0(1.3)    | 1.177          |
| LMC-15    | 0.736(6) | 0.755    | 0.653(3)   | 21.18(3)              | 21.10(9) | 21.07(3) | 1849.4(1)  | 0.300(12) | 22(1)        | 0.979          |
| LMC-23    | 0.422(2) | 0.508    | ...        | 21.05(3)              | 20.92(6) | 20.64(3) | 1137.8(5)  | 0.272(8) | 70(2)        | 1.730          |
| LMC-23-p  | 0.402(2) | 0.508    | ...        | 21.05(3)              | 20.95(6) | 20.64(3) | 1135.8(4)  | -2.48(16) | 16(2)        | 1.410          |

Notes.—The columns of this table list the fit parameters for each event. The values $f_{MB}$, $f_{MB}$, and $f_{CTIO}$ are the blend fractions for the MACHO red- and blue-band and CTIO data sets; $V_M$, $R_M$, $V_{HST}$, and $R_{HST}$ are the calibrated $V$- and $R$-band source star brightnesses for the MACHO (Alcock et al. 1999b) and $HST$ photometry; and $t_0$, $u_0$, and $t_E$ are the standard Paczyński microlensing light-curve fit parameters, where $t_0$ and $u_0$ are the time of peak magnification and the impact parameter, given in units of the Einstein ring radius, and $t_E$ is the Einstein radius crossing time.
blue band is released. The data in Figure 2 have been combined into bins of 8 days, and the data shown in Figure 3 are displayed in bins of 2 days in order to show how well the data fit the model light curve. Since there are as many as five observations per day for this event, a display without binning is easily dominated by the measurements with large error bars and the strength of the signal is easily obscured (as shown in BEL). The DIFIMPHOT photometry provides error bars that are ~75% of the SoDoPHOT error bars, and the fit $\chi^2$/dof values are similar. The CTIO photometry has error bars that average ~42% of the SoDoPHOT error bars with $\chi^2$/dof $\approx$ 1, so the DIFIMPHOT and CTIO photometry clearly support the microlensing model.

Table 3 shows $\Delta \chi^2$, which is the improvement in the fit $\chi^2$ over a constant-brightness model. As we should expect from the size of the error bars, the $\Delta \chi^2$ values are about a factor of 2 larger for the DIFIMPHOT data than for the original SoDoPHOT data. The $\Delta \chi^2$ contribution from the CTIO data is smaller, despite the smaller error bars, because of limited coverage of the CTIO observations.

The one apparent discrepancy between the model and the data is the MACHO blue-band point at the peak of the light curve, a bin that is the average of the six observations from 1994 October 20 and two observations from October 21, when most of the night was clouded out. This high point is caused by three of these eight unbinned measurements, which are between 2 and 3 $\sigma$ above the best-fit curve with the SoDoPHOT photometry. Four of the remaining measurements from these two days are within 1 $\sigma$ of the best-fit curve, and the remaining point is about 1.8 $\sigma$ below the best-fit curve. The three high points are immediately preceded and followed by other observations on the same day that are within 1 $\sigma$ of or below the best-fit light curve. For the DIFIMPHOT photometry, the three high points are between 1.5 and 2.2 $\sigma$ above the best-fit curve, but the point below the curve has moved much closer to the fit curve. Thus, although the DIFIMPHOT photometry reduces the scatter, the average of the eight data points is ~3 $\sigma$ above the curve for both the SoDoPHOT and DIFIMPhot photometry.

All evidence suggests that these high photometry points are due to a systematic photometry error instead of some intrinsic change in blue-band brightness variation. The high points are not correlated in time, and they are not reproduced in the MACHO red band despite the fact that the two MACHO passbands have some overlap in wavelength. This strongly suggests that this high point is due to a systematic photometry error, and the observer’s report suggests a possible cause of such an error. The report from October 20 began with the following description of the observing conditions: “Observing conditions fairly poor for most of the night, drifting cloud patches and a bright moon. Seeing poor, 2"7–3.5." These bright moon conditions did not affect any other part of the magnified part of the light curve, so we conclude that a systematic photometry error related to the bright sky background is the most likely cause of the MACHO blue-band deviation at the peak of the light curve.

The source star lies on the main sequence in the $HST$ color-magnitude diagram (Alcock et al. 2001c; Nelson et al. 2005), and its fitted $R$ magnitude is within 1 $\sigma$ of the $HST$ $R$ magnitude, so the microlensing model correctly predicts the source star color. (The uncertainty in the fit $R_y$ magnitude is the quadrature sum of the fit error [0.04 mag in this case], the 0.04 mag calibration uncertainty [Alcock et al. 1999b], and the uncertainty in the $HST$ $V$ magnitude that the fit is normalized to [0.03 mag]). Table 3 shows $\Delta \chi^2$, the improvement in $\chi^2$ between the microlens model fit and a constant-brightness star fit. While the CTIO data provide substantially more precise photometry than the Mount Stromlo data, the much better light-curve coverage means that most of the strength of the microlensing signal comes from the Mount Stromlo data. The addition of the CTIO data and the DIFIMPHOT photometry strengthens the microlensing signal considerably, from $\Delta \chi^2 = 11,518$ (from the
SoDoPHOT photometry alone) to $\Delta \chi^2 = 27,973$ (from the DIFIMPHOT photometry and CTIO data), with no indication of a deviation from the Paczynski light curve (aside from the apparent systematic error at the light curve peak). The $\Delta \chi^2$ value for LMC-4 with the CTIO and DIFIMPHOT photometry ranks it second among on the MACHO LMC microlensing candidates, behind LMC-14 (Alcock et al. 2001b) and in an approximate tie with LMC-1.

### 3.2. Event MACHO LMC-13

Figures 4 and 5 show the full light curve and a close-up of the LMC-13 light curve, which is displayed in bins of 8 and 4 days, respectively. This event shows the greatest improvement with the DIFIMPHOT photometry, with DIFIMPHOT error bars that are, on average, $\sim$67% of the SoDoPHOT error bars. Also, in this case, CTIO observations were able to begin shortly after the alert, just prior to peak magnification, and the CTIO data show that the light curve follows the microlensing model very accurately from peak magnification down to the baseline. Figure 5 also reveals some apparent photometric errors in the SoDoPHOT MACHO blue-band light curve. Apparent deviations above the fitted curve at the peak and near day 1575 disappear in the DIFIMPHOT data set, as does a low point with small error bars near day 1485. These systematic errors also appear to interfere with the blending estimate from the light-curve fit. An unconstrained fit predicts a source star $V$ magnitude that misses the HST value by about 3.4 times the $1\sigma$ uncertainty, and the fit with the source star magnitude constrained to the HST magnitude increases the $\chi^2$ value of the fit by 7.08, which corresponds to a 2.7 $\sigma$ discrepancy. However, most of the $\chi^2$ is from the MACHO blue-band SoDoPHOT photometry, while the MACHO blue-band DIFIMPHOT photometry has an improved $\chi^2$ with the HST-normalized fit. Thus, we believe that the HST-normalized fit is probably more accurate.

From Table 1, we can see that our fit matches the HST $R$ magnitude exactly, and the source star is on the main sequence of the HST color-magnitude diagram (Nelson et al. 2005). While the DIFIMPHOT photometry reduces the photometry error bars by a factor of 2/3, the CTIO follow-up photometry has error bars that are on average a factor of 5 smaller than the original SoDoPHOT photometry of the MACHO data. The fact that the Paczynski light curve shape is confirmed with photometry 5 times more accurate than the MACHO SoDoPHOT photometry that the event identification was based on provides strong support for the microlensing interpretation of this event.

### 3.3. Event MACHO LMC-15

The full light curve of MACHO LMC-15 is shown in Figure 6 in bins of 8 days, and a close-up is shown in Figure 7, displayed in bins of 2 days. This event was the lowest signal-to-noise event to pass the stricter “criterion A” of the MACHO LMC 5.7 yr analysis. Fortunately, the event was identified well before peak magnification, and very good light curve coverage was obtained from CTIO that filled the gaps in the data from Mount Stromlo. Furthermore, the error bars on the CTIO measurements are, on average, a factor of 4 smaller than the MACHO red-band error bars and a factor of 4.8 smaller than the MACHO blue-band error bars, while the CTIO $\chi^2$/dof is quite reasonable. Thus, the CTIO data provide strong confirmation of the microlensing hypothesis. The DIFIMPHOT photometry, on the other hand, provides only a modest improvement over that of SoDoPHOT, with error bars that are $\sim$85% of the SoDoPHOT error bars in the MACHO red band and $\sim$95% of the SoDoPHOT error bars in the MACHO blue band.

### Table 2

| Event     | MACHO R | MACHO R-DI | MACHO B | MACHO B-DI | CTIO R | CTIO B | CTIO Total |
|-----------|---------|------------|---------|------------|--------|--------|------------|
| LMC-4.....| 5540.5  | 11664.2    | 5977.4  | 11687.8    | 4621.3 | ...    | 27973.3    |
| LMC-13....| 2037.0  | 2377.6     | 1419.2  | 1543.8     | 17521.1|        | 21444.5    |
| LMC-14....| 5229.8  | 6328.6     | 10860.0 | 13868.0    | 69274.8| 64081.7| 153553.0   |
| LMC-15....| 254.3   | 234.2      | 554.0   | 437.8      | 2204.0 | ...    | 3012.2     |

Notes.—MACHO R and MACHO B refer to SoDoPHOT photometry of the MACHO red- and blue-band data, respectively, and MACHO R-DI and MACHO B-DI refer to DIFIMPHOT photometry of a subset of the MACHO data. CTIO R and CTIO-B refer to the CTIO $R$- and $B$-band photometry.

### Table 3

| Event     | $\Delta \chi^2$ Values |
|-----------|------------------------|
| LMC-4.....| 27973.3                |
| LMC-13....| 21444.5                |
| LMC-14....| 153553.0               |
| LMC-15....| 3012.2                 |
Fig. 4.—MACHO and GMAN-CTIO (top) follow-up data, shown in the full light curve for microlensing event LMC-13 (also known as MACHO 96-LMC-1). The solid line shows the best-fit light curve constrained to match the HST $V$-band magnitude, and all data are presented in bins of 8 days. [See the electronic edition of the Journal for a color version of this figure.]

Fig. 5.—MACHO and GMAN-CTIO (top) follow-up data, shown in a close-up of the light curve for microlensing event LMC-13. All data are presented in bins of 4 days, and the two-band MACHO data are presented with the original SoDoPHOT photometry (fourth and fifth panels), as well as photometry from the DIFIMPHOT package (second and third panels). For this event, the photometric noise has been substantially reduced by the DIFIMPHOT photometry. [See the electronic edition of the Journal for a color version of this figure.]

Fig. 6.—MACHO and GMAN-CTIO (top) follow-up data, shown in the full light curve for microlensing event LMC-15 (also known as MACHO 97-LMC-1). The solid line is the best-fit light curve constrained to match the HST $V$-band magnitude, and all data are presented in bins of 8 days. [See the electronic edition of the Journal for a color version of this figure.]

Fig. 7.—MACHO and GMAN-CTIO (top) follow-up data, shown in a close-up of the light curve for microlensing event LMC-15. All data are presented in bins of 2 days, and the two-band MACHO data are presented with the original SoDoPHOT photometry (fourth and fifth panels), as well as photometry from the DIFIMPHOT package (second and third panels). [See the electronic edition of the Journal for a color version of this figure.]
The fit parameters presented in Table 1 indicate that the fit $R$-band magnitude matches the $HST$ value to better than $0.5 \sigma$, and the source star is also on the $HST$ main sequence (Nelson et al. 2005). Also, the constraint that the MACHO blue-band magnitude be fixed to match the $HST$ $V$-band magnitude only causes $\chi^2$ to increase by 0.39, so the fitted $V$-band magnitude also matches the $HST$ $V$-band magnitude to better than 1 $\sigma$.

3.4. Counterexample: Event MACHO LMC-23

Microlensing event candidate MACHO LMC-23 was not detected by the MACHO alert system, so there is no CTIO data for it. Some DIFIMPHOT photometry does exist, with error bars that average $\sim$60% of the SoDoPHOT error bars. It is obvious from Figure 8 that there are deviations from the standard Paczynski light-curve fit. Both the MACHO red- and blue-band data are brighter than the standard Paczynski light-curve fit near days 1123 and 1163, and this occurs for both the SoDoPHOT and the DIFIMPHOT photometry. All four data sets appear to be below the fit curve near day 1180 as well. A microlensing parallax model (Fig. 8, dashed line) provides a much better fit and seems to fit the deviations at days 1163 and 1180. There still appears to be a deviation near day 1123, however.

These qualitative observations are also reflected in the fitted $\chi^2$ values shown in Table 2. For the standard Paczynski light-curve fit, the peak $\chi^2$/dof values are quite large, ranging from 3.229 for the MACHO blue-band SoDoPHOT data to 5.814 for the blue DIFIMPHOT data. For the microlensing parallax model fit (labeled LMC-23-p), the $\chi^2$/dof values drop to reasonable values for the SoDoPHOT photometry (except perhaps the peak $\chi^2$/dof value for the MACHO red-band data), but the DIFIMPHOT values remain high at 2.434 and 3.012 for the MACHO red and blue bands, respectively. This suggests that neither model is likely to be correct, but it is possible that a binary lens model might do better.

Another problem is that the fitted $R$-band magnitudes do not match the $HST$ $R$-band magnitude. They are off by $V - R \approx 0.3$, which is more than 4 $\sigma$ for both the standard and the parallax fit. The source star is on the subgiant branch of the $HST$ color-magnitude diagram (Nelson et al. 2005), but the color at maximum brightness is more consistent with a main-sequence star. On the other hand, the apparent redness of the source star could possibly be explained by blending in the $HST$ images if the lens star were visible and redder than the source, as was the case for event 5 (Alcock et al. 2001e).

However, an additional complication is the fact that the EROS collaboration has observed a subsequent brightening of this star approximately 2500 days after the one observed by MACHO (Glicenstein 2004; Jetzer et al. 2005). Multiple brightening episodes can occur in binary lens or binary source microlensing events, such as MACHO 96-BLG-4 (Alcock et al. 2000a), if the binary lens or source separation is large. However, the probability of detecting such an event decreases in proportion to the binary separation because alignment of both members of the binary with the single lens or source decreases with their separation. Thus, while it might be possible to find a model that could explain this event as lensing, it would require several highly improbable occurrences for this single event: two different types of exotic lensing to explain the light-curve shape in the MACHO data, as well as the brightening seen by EROS, plus a bright lens (or unlikely $HST$ blend by chance superposition). It is much more likely that MACHO LMC-23 is a variable star. This is currently the only MACHO LMC microlens candidate that we have any reason to suspect is not an actual microlensing event.

4. CONFRONTATION OF BEL EVENT CLASSIFICATION WITH ADDITIONAL DATA

The classification of the MACHO LMC events by the MACHO team and BEL are listed in Table 4. This table also provides a “confirmation” column that indicates the implication of additional data for the event classification. Items that support the microlensing interpretation are listed in boldface, and items that tend to contradict the microlensing interpretation are presented in italics. The MACHO verdict refers to the classification given in Alcock et al. (2000c). Events listed as “$\mu$-lens-A” and “$\mu$-lens-B” are candidate microlensing events that passed the strict criterion A or only the looser B criterion. Event 22 did pass criterion B, but a spectrum taken with the Mount Stromlo and Siding Spring Observatories (MSSSO) 2.3 m telescope revealed that the source was an emission-line galaxy at $z = 0.233$ (T. Axelrod 2000, private communication).

Table 4 indicates that our expectation that the BEL event selection method is unreliable has been borne out by our new data and analysis. Of the four events that we have analyzed, the only one that BEL classify as microlensing is event 23, which is most likely a variable star. The other three events they classify as nonmicrolensing, but the new data confirm the microlensing interpretation, again contradicting BEL. These four events probably provide the best test of the BEL method, because these data had not been previously published, except in a Ph.D. thesis (Becker 2000), and so the additional data were probably not seen by BEL when they were designing their method. In contrast, the original MACHO analysis (Alcock et al. 2000c) is confirmed for the three events with additional photometric data during the microlensing event, but not for event 23.
The complete MACHO analysis identifies 25 events as either microlensing candidates or supernovae. (The events are numbered 1 and 4–27, as events 2 and 3 from the first-year analysis [Alcock et al. 1996a] do not make the 5 yr cuts.) Of these 25 events, MACHO classifies 16 as microlensing candidates, 8 as background supernovae, and 1 as either an active galactic nucleus or a peculiar background supernova. The BEL analysis identifies 10 of these events as microlensing, 5 as supernovae, and 9 as neither. Event 9, the LMC binary lens event (Bennett et al. 1996; Alcock et al. 2000a), is not considered by BEL. The BEL analysis agrees with MACHO in the classification of seven events as microlensing and four events as supernovae. We now examine these classifications in light of other, non–light curve data.

Of the seven events identified by both MACHO and BEL as microlensing, event 1 has a follow-up spectrum consistent with the microlensing interpretation (della Valle 1994), and event 5 has been confirmed by HST observations that identified the lens star in the Milky Way disk and provided the first complete solution for a microlensing event (Alcock et al. 2001e; Drake et al. 2001; Gould et al. 2004; Nguyen et al. 2004). Event 14 was confirmed with high signal-to-noise GMAN follow-up data, which also enabled measurement of the microlensing “xallarap” effect (light-curve oscillations due to the orbit of a binary source star) and the determination that the lens is close to the LMC (Alcock et al. 2001b). We argue in § 5 that events 1 and 25 are very likely to be microlensing as well, but we have seen that event 23 is probably a variable star, although it was identified as a microlensing candidate by both MACHO (Alcock et al. 2000c) and BEL. Thus, four of these seven events can be considered to be confirmed, and one is rejected.

Three events are identified by BEL, but not MACHO, as microlensing: events 10, 22, and 24. They all have highly asymmetric light curves that suggest a nonmicrolensing origin, although in the case of event 22, the asymmetry can be fitted by a microlensing parallax model with plausible parameters. The MACHO photometry of event 10 is a near-perfect fit to a supernova Type Ia light curve, and so this event is clearly a background supernova. It is near the blue end of the Type Ia supernova color distribution, and this is probably why BEL’s supernova test fails.

Event 24 is also fitted much better by a supernova Type Ia light curve than by standard microlensing, so it was also rejected as a microlensing candidate. The quality of the Type Ia fit for event 24 is poor, however, so it is more likely that this event is a Type II supernova. The source locations for each of these events correspond to background galaxies. For event 24, the galaxy is visible in the MACHO images, while the source “star” for event 10 is revealed to be a compact galaxy in HST images (Alcock et al. 2001c). The source for LMC-22 appears slightly extended in a higher resolution CTIO 4 m frame, and a spectrum of the source indicates that it is probably an active galaxy. Thus, the microlensing interpretation is rejected for all three of these events classified by BEL, but not MACHO, as microlensing.

Of the nine events classified by BEL as neither microlensing nor supernovae, MACHO classifies two as supernovae and seven as microlensing (events 4, 7, 8, 13, 15, and 18). In §§ 3.1–3.3, we have shown that the microlensing interpretations of three of these events (4, 13, and 15) are strongly confirmed by the additional photometry we have presented, but there exist no follow-up data that shed light on the other events. However, event 8 is the lone event in the center of the LMC bar, where the LMC self-lensing probability is highest (Mancini et al. 2004), so it seems likely that this event is microlensing, as well. Thus, the BEL classification fails for three of these events and is likely to fail for one other.

### Table 4

| Event | MACHO Verdict | BEL Verdict | Confirmation | Mancini et al. Lens Type |
|-------|---------------|-------------|--------------|-------------------------|
| 1     | μlens-A       | μlens       | Clump giant  | Non-LMC                 |
| 4     | μlens-A       | Variable    | CTIO+DIP phot.| Non-LMC                 |
| 5     | μlens-A       | μlens       | Lens ID      | MW disk                 |
| 6     | μlens-A       | μlens       | ...          | LMC                     |
| 7     | μlens-A       | Variable    | ...          | Non-LMC                 |
| 8     | μlens-A       | Variable    | ...          | LMC                     |
| 9     | μlens-B       | ...         | Caustic binary | LMC                     |
| 10    | SN            | μlens       | HST: galaxy  | ...                     |
| 11    | SN            | SN          | HST: galaxy  | ...                     |
| 12    | SN            | SN          | HST: galaxy  | ...                     |
| 13    | μlens-A       | Variable    | CTIO+DIP phot.| LMC                     |
| 14    | μlens-A       | μlens       | CTIO+DIP phot.| LMC                     |
| 15    | μlens-A       | Variable    | CTIO+DIP phot.| Non-LMC                 |
| 16    | SN            | ...         | CTIO: galaxy  | ...                     |
| 17    | SN            | SN          | CTIO: galaxy  | ...                     |
| 18    | μlens-A       | Variable    | ...          | Non-LMC                 |
| 19    | SN            | SN          | ...          | ...                     |
| 20    | μlens-B       | SN          | ...          | ...                     |
| 21    | μlens-A       | μlens       | ...          | Non-LMC                 |
| 22    | B             | μlens       | MSSSO: galaxy | ...                     |
| 23    | μlens-A       | μlens       | Variable     | ...                     |
| 24    | SN            | μlens       | MACHO: galaxy | Non-LMC                 |
| 25    | μlens-A       | μlens       | Clump giant  | Non-LMC                 |
| 26    | SN            | Variable    | ...          | ...                     |
| 27    | μlens-B       | Variable    | ...          | ...                     |

**Notes.**—The event classification results of MACHO and BEL are compared to the results of additional data that can confirm or reject each event. Confirmed microlensing events have boldface entries in the confirmation column, and rejected microlensing candidates have entries in italics.
It seems clear that the only time when BEL’s event classification scheme appears to succeed more often than not is when it agrees with the MACHO classification. We have shown that their identification of events as “nonmicrolensing” fails for the three events with new data presented in this paper, and in most cases in which they disagree with MACHO, additional data strongly suggest that the BEL results are wrong. We can only conclude that BEL’s selection method does not provide any help in separating real microlensing events from other types of variability that mimic microlensing. However, this does not mean that neural networks cannot improve on the MACHO analysis. Instead, as we have argued in § 1.1, BEL’s method fails because of the weak set of statistics that they relied on. A neural network that uses the more powerful light-curve fitting–based statistics used by MACHO might indeed offer an improvement.

5. DISCUSSION AND CONCLUSIONS

The MACHO Project’s 5.7 yr LMC analysis has identified a set of 16 candidate LMC microlensing events after removing the background supernovae. In this paper, we have analyzed additional photometry from GMAN follow-up observations with the CTIO 0.9 m telescope, as well as DIFIMPHOT photometry of the original Mount Stromlo MACHO observations for three of these events: MACHO LMC-4, 13, and 15. This additional photometry has errors that are smaller than the original MACHO photometry by a factor of 1.1–1.5 (for DIFIMPHOT) and of 2.4–5 (for the GMAN CTIO photometry) and improves the light-curve time coverage for these events. All three light curves with the improved photometry are well fitted by a standard Paczyński microlensing model.

For two of the three light curves, the fit accurately predicts both the V- and R-band magnitudes from high-resolution HST observations of the microlensed source star. For the other event, LMC-13, the unconstrained Paczyński fit predicts a V-band magnitude that differs by the HST magnitude by 2.7 σ, but the difference between the DIFIMPHOT and SoDoPHOT photometry of the Mount Stromlo data suggests that this may be affected by low-level systematic photometry errors. A Paczyński light-curve fit constrained to the HST V magnitude accurately predicts the HST R magnitude for event LMC-13. Thus, it is fair to say that the additional photometry provides a strong confirmation of the microlensing interpretation of these three events.

In addition to these events, there are several other of the MACHO LMC microlensing candidates for which the microlensing interpretation seems very secure. Event 14 has also been confirmed with GMAN photometry that provides evidence of the xallarap effect (Alcock et al. 2001b), and event 5 is the first microlensing event in which the lens has been detected (Alcock et al. 2001c; Drake et al. 2004; Nguyen et al. 2004) and has been completely solved, yielding the mass, transverse velocity, and distance of the lens (Gould et al. 2004). The consistency of the microlensing mass determination with the lens star brightness and colors provides a strong confirmation of the microlensing model for this event.

Events LMC-1 and 25 are the two events that clearly have red clump giant source stars (della Valle 1994; Alcock et al. 2000c; Nelson et al. 2005), and such stars have not exhibited the type of variability that could be confused with microlensing (Keller et al. 2002), as observed in EROS LMC-1 and 2 and MACHO LMC-2 and 23 (Alcock et al. 1997; Ansari et al. 1995; Beaulieu et al. 1995; Lasserre et al. 2000; Glicenstein 2004; Jetzer et al. 2005). Finally, event MACHO LMC-9 is well fitted by a binary lens model (Bennett et al. 1996; Alcock et al. 2000a) and has a light-curve shape that is different from other known forms of variability with the very rapid brightness variation that is characteristic of a binary lens caustic crossing.

So, out of the 16 MACHO LMC microlensing candidates, five have been confirmed with additional data, and another three appear very likely to be microlensing. Of the five events that have been confirmed with additional data, four have been selected by a completely independent method: their discovery by the MACHO alert system. All four of these events have been confirmed to be microlensing, which suggests that most of the MACHO LMC microlensing candidates are indeed due to microlensing. Nevertheless, the example of MACHO LMC-23 suggests that some caution is warranted regarding the interpretation of the seven remaining MACHO LMC microlensing events that have not yet been confirmed.

It is instructive to consider the results of Mancini et al. (2004), who have done detailed predictions of the properties of LMC self-lensing events on the basis of some of the latest models of the LMC. (Their classifications are listed in Table 4.) They identify four of the MACHO events that are good LMC self-lensing candidates: events 6, 8, 13, and 14. A straightforward extension of their analysis also adds the binary lens event, 9, to this list. This identification is strengthened by independent light-curve analyses that suggest that events 9 and 14 both have lenses residing in the LMC (Bennett et al. 1996; Alcock et al. 2001b). Of the remaining 10 events, the event 5 lens star has been shown to be a disk star. It is most likely a member of the thick disk, but thin-disk membership cannot be ruled out (Gould et al. 2004). Event 20 is also a disk lens candidate because it appears to be blended with a star that is much redder than other LMC stars of similar magnitude (Alcock et al. 2000c). (If event 20 is also a disk lens, this would give us a total of two disk events, when a total of 0.75 are expected from the combined thin and thick disks. The Poisson probability of detecting two or more disk events when 0.75 are expected is 17%.) This leaves eight events as halo lens candidates: events 1, 4, 7, 15, 18, 21, 25, and 27. Two of these halo lens candidates (events 4 and 15) are confirmed by the photometry and light-curve fitting presented here, and two others (events 1 and 25) are considered “solid” events because of their red clump giant source stars. Thus, there is little difference between the quality of the different categories of events. Thus, the confirmed events appear to be distributed about evenly among the disk, halo, and LMC self-lensing candidate events.

Our qualitative conclusion is that the puzzle of the excess LMC lensing events remains unresolved. Our knowledge of the Galactic disk and LMC suggests that most of the lenses must reside in a previously undiscovered population, and the Milky Way halo is the natural location for this, since the halo’s mass is largely unaccounted for. However, such a population presents a number of problems if it is composed of known objects such as white dwarfs. The leading alternative explanation is that LMC self-lensing dominates, but this possibility gets no significant observational support from detailed LMC models or from the properties of the microlensing events themselves. (See Sahu [2003] for a different point of view.)

A resolution of this puzzle will probably require additional data so that the distance to a representative sample of LMC lensing events can be determined. This could come from the microlensing key project for the Space Interferometry Mission (SIM; Unwin & Turiyshev 2002), or from a Deep Impact mission extension (DIME; Cook et al. 2003), which would use the 30 cm telescope on the Deep Impact spacecraft to make microlensing parallax observations from a heliocentric orbit (Gould...
1995a), if it is approved. Microlensing experiments toward other lines of sight could also shed some light on this issue (de Jong et al. 2004; Calchi Novati et al. 2005; Paulin-Henriksson et al. 2003). In addition, the SuperMACHO (Becker et al. 2005) and MOA-II (Microlensing Observations in Astrophysics; Muraki 2004) surveys expect to substantially increase the detection rate of LMC microlensing events in order to provide alerts for SIM and DIME and to measure the spatial variation of the microlensing optical depth across the face of the LMC.

D. P. B. was supported by grants AST 02-06189 from the NSF and NAGS-13042 from NASA.

REFERENCES

Afonso, C., et al. 2003a, A&A, 400, 951
———. 2003b, A&A, 404, 145
Albrow, M. D., et al. 1999, ApJ, 522, 1011
Alcock, C., et al. 1993, Nature, 365, 621
———. 1996a, ApJ, 461, 84
———. 1996b, ApJ, 463, L67
———. 1997, ApJ, 486, 697
———. 1998, ApJ, 499, L9
———. 1999a, ApJ, 521, 602
———. 1999b, PASP, 111, 1539
———. 2000a, ApJ, 541, 270
———. 2000b, ApJ, 541, 734 (erratum 557, 1005 [2001])
———. 2000c, ApJ, 542, 281
———. 2001a, ApJ, 550, L19
———. 2001b, ApJ, 552, 259
———. 2001c, ApJ, 552, 582
———. 2001d, ApJS, 136, 439
———. 2001e, Nature, 414, 617
Alves, D. R. 2004, ApJ, 601, L151
Ansari, R., et al. 1995, A&A, 299, L21
Aubourg, E., et al. 1993, Nature, 365, 623
Beaulieu, J. P., et al. 1995, A&A, 299, 168
Becker, A. C. 2000, Ph.D. thesis, Univ. Washington
Becker, A. C., et al. 2005, in IAU Symp. 225, Impact of Gravitational Lensing on Cosmology, ed. Y. Mellier & G. Meylan (Cambridge: Cambridge Univ. Press), in press (astro-ph/0409167)
Belokurov, V., Evans, N. W., & Le Du, Y. 2003, MNRAS, 341, 1373
———. 2004, MNRAS, 352, 233
Bennett, D. P., et al. 1996, Nucl. Phys. B Proc. Suppl., 51, 152
Bond, I. A., et al. 2004, ApJ, 606, L155
Brook, C. B., Kawata, D., & Gibson, B. K. 2003, MNRAS, 343, 913
Calchi Novati, S., et al. 2005, preprint (astro-ph/0504188)
Cook, K., et al. 2003, BAAS, 35, 14302
de Jong, J. T. A., et al. 2004, A&A, 417, 461
della Valle, M. 1994, A&A, 287, L31
Drake, A. J., Cook, K. H., & Keller, S. C. 2004, ApJ, 607, L29
Evans, N. W., & Belokurov, V. 2005, in The Identification of Dark Matter, ed. N. J. C. Spooner & V. Kudryavtsev (Singapore: World Scientific), in press (astro-ph/0411222)
Evans, N. W., & Kerins, E. 2000, ApJ, 529, 917
Flynn, C., Holopainen, J., & Holmberg, J. 2003, MNRAS, 339, 817
García-Berro, E., Torres, S., Isen, J., & Burkert, A. 2004, A&A, 418, 53
Gates, E. I., & Gyuk, G. 2001, ApJ, 547, 786
Glicenstein, J.-F. 2004, EROS Results, Hawaii Microlensing Workshop 2004 (Nagoya: Solar-Terrestrial Environment Laboratory), http://www.stelab.nagoya-u.ac.jp/hawaii/
Gould, A. 1995a, ApJ, 441, L21
Gould, A. 1995b, ApJ, 441, 77
Gould, A., Bennett, D. P., & Alves, D. R. 2004, ApJ, 614, 404
Griest, K., & Thomas, C. L. 2005, MNRAS, 359, 464
Gyuk, G., Dalal, N., & Griest, K. 2000, ApJ, 535, 90
Jetzer, P., Milisavljević, A., & Tisserand, P. 2005, in IAU Symp. 225, Impact of Gravitational Lensing on Cosmology, ed. Y. Mellier & G. Meylan (Cambridge: Cambridge Univ. Press), in press (astro-ph/0409496)
Keller, S. C., Besseill, M. S., Cook, K. H., Geha, M., & Sphers, D. 2002, AJ, 124, 2039
Lasserre, T., et al. 2000, A&A, 355, L39
Lennon, D. J., Mao, S., Fuhrmann, K., & Gehren, T. 1996, ApJ, 471, L23
Mancini, L., Calchi Novati, S., Jetzer, P., & Scarpetta, G. 2004, A&A, 427, 61
Minniti, D., Vandehei, T., Cook, K. H., Griest, K., & Alcock, C. 1998, ApJ, 499, L175
Muraki, Y. 2004, Search for Dark Stars by the Microgravitational Lens Method, Hawaii Microlensing Workshop 2004 (Nagoya: Solar-Terrestrial Environment Laboratory), http://www.stelab.nagoya-u.ac.jp/hawaii/
Nelson, C., et al. 2005, AJ, submitted
Nguyen, H. T., Kallivayalil, N., Werner, M. W., Alcock, C., Patten, B. M., & Stern, D. 2004, ApJS, 154, 266
Nikolaev, S., Drake, A. J., Keller, S. C., Cook, K. H., Dalal, N., Griest, K., Welch, D. L., & Kanbur, S. M. 2004, ApJ, 601, 260
Paczynski, B. 1986, ApJ, 304, 1
Paulin-Henriksson, S., et al. 2003, A&A, 405, 15
Popowski, P., et al. 2005, ApJ, in press (astro-ph/0410319)
Rahvar, S. 2005, MNRAS, 356, 1127
Sahu, K. C. 1994, Nature, 370, 275
———. 2003, in Proc. STScI Symp. 15, The Dark Universe: Matter, Energy and Gravity, ed. M. Livio (Cambridge: Cambridge Univ. Press), 14
Spagna, A., Carollo, D., Lattanzi, M. G., & Buccicrelli, B. 2004, A&A, 428, 451
Stetson, P. B. 1994, PASP, 106, 250
Sumi, T., et al. 2003, ApJ, 591, 204
Tomanyan, A. B., & Crotts, A. P. S. 1996, AJ, 112, 2872
Torres, S., García-Berro, E., Burkert, A., & Isern, J. 2002, MNRAS, 336, 971
Udalski, A., Szymański, M., Kubiak, M., Krzemiński, M., Mateo, M., Preston, G. W., & Paczynski, B. 1993, Acta Astron., 43, 289
Udalski, A., et al. 1994, Acta Astron., 44, 165
Uglesich, R. R., Crotts, A. P. S., & Tomaney, A. B. 1996, AJ, 112, 2872
Welch, D. L., & Kanbur, S. M. 2004, ApJ, 612, 877
Winn, S., & Turshev, S., eds. 2002, Science with the Space Interferometry Mission (Caltech: JPL), http://planetquest.jpl.nasa.gov/Navigator/library/science_/AAS_Jan02.pdf
Weinberg, M. D. 2000, ApJ, 532, 922
Woźniak, P. R., Udalski, A., Szymański, M., Kubiak, M., Pietrzyński, G., Sozzi, G., & Zebrun, K. 2001, Acta Astron., 51, 175
Wu, X. 1994, ApJ, 435, 66