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The SuperMACHO Microlensing Survey

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Abstract. We present the first results from our next-generation microlensing survey, the SuperMACHO project. We are using the CTIO 4m Blanco telescope and the MOSAIC imager to carry out a search for microlensing toward the Large Magellanic Cloud (LMC). We plan to ascertain the nature of the population responsible for the excess microlensing rate seen by the MACHO project. Our observing strategy is optimized to measure the differential microlensing rate across the face of the LMC. We find this derivative to be relatively insensitive to the details of the LMC's internal structure but a strong discriminant between Galactic halo and LMC self lensing. In December 2003 we completed our third year of survey operations. 2003 also marked the first year of real-time microlensing alerts and photometric and spectroscopic followup. We have extracted several dozen microlensing candidates, and we present some preliminary light curves and related information. Similar to the MACHO project, we find SNe behind the LMC to be a significant contaminant - this background has not been completely removed from our current single-color candidate sample. Our follow-up strategy is optimized to discriminate between SNe and true microlensing.

1. Introduction

Paczynski (1986) first suggested searching for Galactic dark matter in the form of MACHOs (MAssive Compact Halo Objects) by searching for gravitational microlensing of stars in the Magellanic Clouds. Several groups followed this suggestion and established microlensing searches that have led to a wealth of information on stellar variability and constraints on Galactic structure. In particular, the MACHO group reported 13-17 microlensing events toward the LMC (Alcock et al. 2000) with event timescales (Einstein diameter crossing time $\hat{t}$) ranging from 34 to 230 days. This study led to an estimated microlensing optical depth toward the LMC of $\tau = 1.2^{+0.4}_{-0.3} \times 10^{-7}$. If we assume that MACHOs are responsible for this optical depth, then a typical Galactic halo model allows for a MACHO halo fraction of 20% (95% confidence interval of 8%-50%) with MACHO masses ranging between 0.15 and 0.9 $M_{\odot}$. The EROS group found 3 LMC events (Aubourg et al. 1993, Renault et al. 1997, Lasserre et al. 2000), in agreement with the findings of the MACHO group†. Notably, none of the surveys toward the LMC have detected events with timescales 1hr $\leqslant \hat{t} \leqslant$ 10days. This complete lack of short timescale events puts a strong upper limit on the abundance of low-mass dark matter objects: objects with masses $10^{-7} M_{\odot} < M < 10^{-3} M_{\odot}$ make up less than 25% of the halo dark matter. Further, less than 10% of a standard spherical halo is made of MACHOs

† See however the paper by P. Jetzer in these proceedings. He reports long–term EROS monitoring has detected secondary microlensing–like peaks in one previous EROS and one previous MACHO event, suggesting stellar variability might play a role in the observed event rate. Jetzer also reports the most recent EROS optical depth estimates are well below that reported by the MACHO collaboration

in the $3.5 \times 10^{-7} M_\odot < M < 4.5 \times 10^{-5} M_\odot$ mass range (Alcock et al. 1998). Surveys towards M31 are also yielding a clear microlensing signal, although the overall number of events is low and it is still difficult to distinguish between M31 self and halo lensing (POINT-AGAPE, Paulin-Henriksson & Novati 2004; VATT/Columbia, Uglesich et al. 2004).

Despite these constraints on the MACHO halo fraction, the reported microlensing event rate toward the LMC significantly exceeds that expected from known visible components of our Galaxy. This rate depends on the spatial, mass, and velocity distribution of the lenses. The primary observable quantity in any given microlensing event, its duration, depends upon a combination of all three of these parameters. Any conclusion about the spatial location of the lens population therefore depends upon the assumptions made about its mass and velocity. In cases where the lightcurve exhibits a departure from the point-source, point-lens, inertial motion approximation (due to e.g. a binary lens, a binary source or parallax), this degeneracy can be lifted.

In light of the inherent difficulty in locating the LMC lenses down the line of sight, we are left with a variety of possible explanations for the excess LMC event rate which includes: (1) lensing by a population of MACHOs in the Galactic Halo, (2) lensing by a previously undetected thick disk component of our Galaxy, (3) disk-bar or bar-bar self-lensing of the LMC, or (4) lensing by an intervening dwarf galaxy or tidal tail. Due to the limited number of events observed to date it is not yet clear which scenario or combination of scenarios explains the observed lensing.

Each of these dominant lens populations produces a signature in the microlensing optical depth as a function of position across the face of the LMC. Using recent papers by van der Marel & Cioni (2001), van der Marel (2001), and van der Marel et al. (2002) on the structure and kinematics of the LMC, Mancini et al. (2004) derive and compare these spatial signatures for a variety of lens populations. In particular, Galactic halo microlensing should produce a slight optical depth gradient across the face of the LMC, varying by ~ 6 %. LMC self–lensing tends to produce a steep gradient in optical depth around a central peak. However, the reported MACHO and EROS events only coarsely sample these optical depth contours. To do so finely, and in turn constrain the nature of the lensing populations(s), requires an order of magnitude increase in the number of detected events.

2. The SuperMACHO Survey

The SuperMACHO Project† is an ongoing five-year microlensing survey of the LMC that is being carried out with the specific goal of determining the location of the objects that produce the observed microlensing events (Stubbs 1999). This will be achieved by adding more events to the overall sample, allowing comparisons/distinctions to be drawn between the measured optical depth variation and Galactic–LMC lensing models. We have been allocated 150 half-nights, distributed over 5 years, on the Cerro Tololo Inter-american Observatory (CTIO) Blanco 4m telescope through the NOAO Survey Program. The survey started in 2001 and will run through 2005 ‡.

Observations are carried out every other night in dark time during the months of October, November, and December, when the LMC is most accessible from CTIO. We use the $8K \times 8K$ MOSAIC II CCD imager with a FOV of 0.33 square degree. The 8

† http://www.ctio.noao.edu/∼supermacho

‡ We note that we have waived proprietary data access rights, and that the SuperMACHO survey images are accessible through the NOAO Science Archive on the NOAO web site at ftp://archive.tuc.noao.edu/pub/

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SITe $2K \times 4K$ CCDs are read out in dual-amplifier mode (i.e. different halves of each CCD are read out in parallel through separate amplifiers) to increase our observing efficiency. In order to maximize the throughput we use a custom-made broadband filter (VR filter) from 500nm to 750nm. The atmospheric dispersion corrector on the Mosaic imager allows for the use of this broad band without a commensurate PSF degradation. We monitor 68 LMC fields, using difference image analysis to search for variability. Our combination of exposure times and telescope aperture means that we are sensitive to changes in brightness equivalent to the brightness of a $\sim 23^{rd}$ magnitude star. Rest et al. (2004) estimate that we are sensitive to this level of variability in 50–100 million stars.

Our data are reduced immediately after acquisition using an automated data reduction pipeline. Images are cross–talk corrected and WCS calibrated as a Multi–Extension Fits file, and afterwards separated into 16 separate images, one for each amplifier, for further parallel processing. The images are calibrated, their PSFs are modeled using a modified version of the `DOPHOT` program, and are then passed to an image registration module (currently based on the SWarp† program) that astrometrically aligns each with a reference template image. The input and template images are then differenced using a modified version of the Alard (2000) algorithm (Becker et al. 2004). `DOPHOT` is used to detect new objects using the PSF derived from the input images. For any new objects detected, forced–position photometry is applied to the entire time–series of images containing the position of the variability. Cuts are applied to these time series to look for true variability, and candidate events passing these cuts are posted to an internal web page for visual review. Events passing this stage are posted to a public web page.

2.1. *LMC Fields*

Figure 1 shows our distribution of fields on the LMC. For the purpose of our analysis, we have arranged these into 5 sets of fields, each of which contain roughly the same number of LMC source stars. Figure 1 also shows the expected cumulative and differential event distribution amongst these fields sets. For each set, we show the expected number of events for 3 lensing model populations. The black points show the number and fraction of events expected from the LMC self–lensing model of Zhao & Evans (2000), the red points are for Galactic halo lensing adopting the Alcock et al. (2000) results, and the blue for the LMC self–lensing model of Nikolaev (2003, private communication). In addition, model parameters such as the LMC luminosity function (LF), disk–bar separation, and bar mass fraction are varied to add a dispersion in the expected number of events that reflects our uncertainty in the physical system. The lower panel shows the fraction of all microlensing events detected in each set. The smaller dispersion indicates this metric is much less sensitive to the model parameters while still retaining sensitivity between self and Galactic halo lensing models. If the MACHO fraction is significantly lower than the Alcock et al. (2000) results (P. Jetzer, these proceedings; A. Milsztajn, private communication), the cumulative number of events expected will change, but the differential rate should not. In addition, field sets 4 and 5 are almost uniquely sensitive to the Galactic halo MACHO fraction, avoiding complications which might result from an admixture of lensing populations.

The lowest Galactic halo lensing expectation value for the field set 5 differential event rate is 0.15. As a particular test to exclude LMC self–lensing models, and assuming the total and fractional number of events expected from the above halo lensing scenario, we next note the upper limit on the field set 5 differential measurement for all Zhao self–lensing models is 0.014. We can exclude these models with 99% and 99.5% confidence

† http://terapix.iap.fr/soft/swarp

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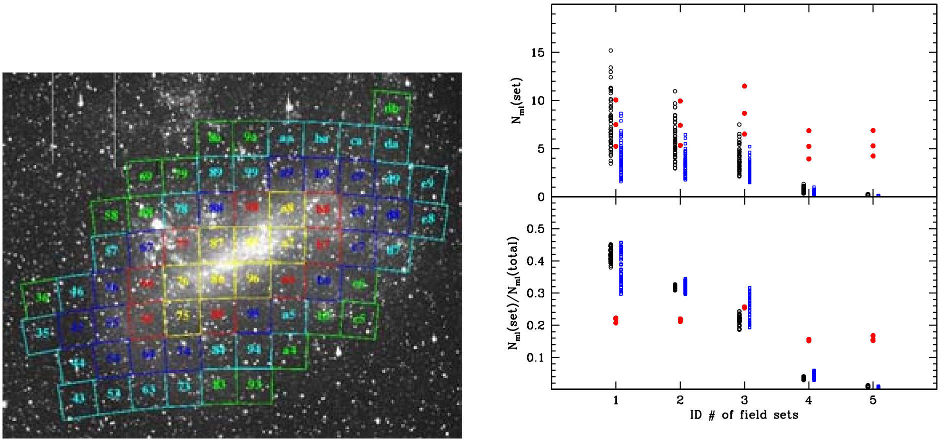

Figure 1. *Left* : Distribution of SuperMACHO fields across the face of the LMC. For the purpose of analysis, these fields are divided into sets comprising roughly equal numbers of source stars. Field sets 1–5 are shown in *yellow*, *red*, *dark blue*, *light blue*, and *green*, respectively, and are arranged in concentric rings around a fiducial center. *Right* : Cumulative and differential distribution of microlensing events across the field sets, for 3 different microlensing models. For each field set, the *black* points represent Zhao & Evans LMC self–lensing models, the *red* are for Galactic halo lensing assuming the MACHO results, and the *blue* are for Nikolaev LMC self–lensing. The distributions are ordered as above and horizontally offset for clarity. Uncertainly in the expected number of events comes from varying model parameters. The bottom panel shows that the differential event rate is less sensitive to these parameters. In particular, field sets 4 and 5 are highly sensitive to Galactic halo MACHOs.

if we observe a differential rate larger than 0.11 and 0.13, respectively. Similarly for the Nikolaev models, the maximum differential rate is 0.011, thus they can be excluded at 99.5% confidence if the observed differential event rate is bigger than 0.12. Galactic halo lensing is highly favored if the measured field set 5 event fraction is $\gtrsim 0.1$.

2.2. *Event Candidates : 2003*

We detected approximately 10 high quality microlensing events in 2003, two of which are shown in Figure 2. We also found nearly 70 supernovae (SNe) in galaxies behind the LMC, two of which are shown in Figure 3. These are frequently distinguishable by the presence of their host background galaxy in our images. At high signal–to–noise (S/N), the lightcurves are also clearly asymmetric, in the particular sense that the rising slope is steeper than the falling slope. At low S/N, however, it is more difficult to distinguish the two populations of events. We note that in 2003 we also obtained spectroscopy of approximately 25 microlensing candidates, which is used to both confirm and reject particular events as microlensing. Spectroscopy during the event is arguably the most discriminating observation, and we regard this campaign as an integral part of the survey.

2.3. *SuperMACHO 2004–2005*

For the upcoming observing seasons, we will be modifying our observing strategy and allocating photometric and spectroscopic resources to define concretely the characteristics of microlensing and supernovae in our data. Our alert and followup routine will take the following form :

• Alert based upon flat prior baseline, rising flux, and other characteristics of the time–series. Based upon our experiences in 2003, we are confident we can detect variability well before peak.

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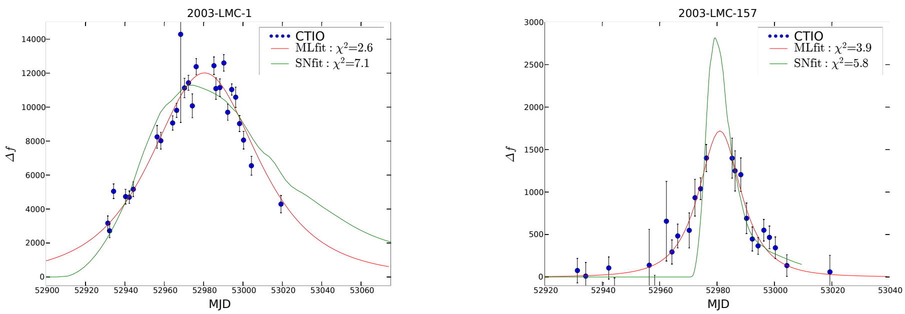

Figure 2. Two microlensing candidates from 2003. 2003–LMC–1 was a low magnification event ($u_{min} = 1.5$) on a likely clump–giant star, and yielded a peak magnitude of $VR = 18.9$. 2003–LMC–157 is a more typical event. The lensed source star is unknown, as there is no obvious counterpart in our template image. We can limit the impact parameter to be $u_{min} < 0.8$. The observed peak change in flux yields $\Delta VR = 23.1$.

• 1st SN discriminant : Presence/absence of host galaxy in template image.

• 2nd SN discriminant : Multi-color observations from the 4–m before peak. $VR - I$ vs $B - VR$ colors will yield a distance from the stellar locus as well as an early reference point for color evolution studies.

• 3rd SN discriminant : Snapshot high–resolution imaging from Gemini South or Magellan. This imaging will also serve as a finding chart and/or resource for nod–and–shuffle planning for future spectroscopy, if needed. This will also yield an additional check for background galaxies, as well as another epoch of color information in which the sources are less blended.

• Objects passing the above cuts are considered good candidates for microlensing, and will be submitted to Gemini South or Magellan for spectroscopic followup near peak.

• For those events where we are unable to obtain spectroscopy, we will instead obtain additional multi–color images during the event, especially near peak, to constrain color evolution. The color–evolution of SNe is 2 magnitudes in $VR - I$ before the peak, and nearly 2 magnitudes in $B - VR$ afterwards. For microlensing, the color of the variability should remain in place on the stellar locus. In addition, SNe $VR - I$ colors at peak are significantly removed from the stellar locus, and serve as a powerful single–epoch discriminant. This photometric followup will occur using the 4–m and other global resources.

3. Conclusions

The SuperMACHO survey intends to constrain the location of the objects contributing to the excess microlensing signal towards the LMC. By increasing the overall number of events by a factor of several over the current event count, we will be able to more faithfully sample the variation of the microlensing optical depth across the face of the LMC, and thus constrain the nature of the lenses yielding this signal. As of 2003, the survey is detecting and following up events in real–time. We find that background supernovae are our most prominent source of contamination. Our survey and follow–up strategy are designed to obtain multi–color and spectroscopic information of on–going events to discriminate true microlensing from the sources of background. Spectroscopic information is necessary to absolutely confirm the normal stellar nature of candidate microlensing sources, and to rule out intrinsic variability as the source of a detected event.

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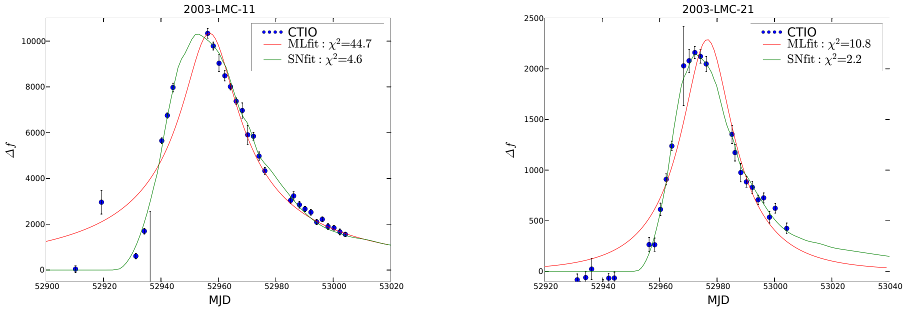

Figure 3. Two supernova candidates from 2003. We obtained spectroscopy of event 2003–LMC–11, indicating a Type Ia SN at a redshift of $z = 0.25$. 2003–LMC–21 is determined to be a likely SN due to the good fit to SNe lightcurve templates compared to the best microlensing fit ($\Delta\chi^2 = 8.6$) and the clear lightcurve asymmetry.

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