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Determination of Microlensing Selection Criteria for the SuperMACHO Survey

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Abstract.
The SuperMACHO project is a 5 year survey to determine the nature of the lens population responsible for the excess microlensing rate toward the Large Magellanic Cloud observed by the MACHO project [1]. The survey probes deeper than earlier surveys unveiling many more extragalactic contaminants, particularly type Ia supernovae and active galactic nuclei. Using $\sim 10^7$ simulated light curves of both microlensing events and type Ia supernovae we determine selection criteria optimized to maximize the microlensing detection efficiency while minimizing the contamination rate from non-microlensing events. We discuss these simulations and the selection criteria.

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MICROLENSING IN THE MAGELLANIC CLOUDS

One of the outstanding questions in modern cosmology concerns the composition of the Dark Matter within our own galaxy. Following the suggestion of Paczynski [2], microlensing surveys of the Magellanic Clouds conducted in the 1990s sought to determine the fraction of the dark matter in the Galactic halo comprised of MAssive Compact Halo Objects (MACHOs) [1, 3]. These studies demonstrated that the majority of the dark matter is not contained in MACHOs, though the findings of the MACHO project suggested a large excess population of lenses toward the clouds with total mass as high as $\sim 10^{11}$ $M_{\odot}$, comparable to the entire Milky Way disk.

In the decade since the initial microlensing surveys, the results remain a subject of active research. Indications of variability in sources of events classified as microlensing by the MACHO and EROS projects [4] has led to a reanalysis of the full MACHO data set that still finds the microlensing rate to be in excess of that expected from known populations at the 99.98% confidence level [5]. These findings suggest the possibility of non-microlensing contamination in the initial candidate sets and a need for new data.

THE SUPERMACHO PROJECT

The SuperMACHO project seeks to clarify the microlensing results by monitoring sources in the Large Magellanic Cloud (LMC) deeper into the main sequence and spread across its face [see 6]. The survey was carried out during 150 half-nights between 2001-2006 on the Cerro Tololo InterAmerican Observatory's Blanco 4m telescope using the MOSAIC-II imager. Observations were made each year between September and the following January every other night except during bright time. The survey was conducted using a single, custom, wide-band, optical filter that covers the wavelength range from 5000–7500 Å. We use difference imaging [see 7, 8] to identify sources of variable flux, and all light curve analysis is done in "difference flux" space. Miknaitis et al. [9] provide a description of the data reduction pipeline, and Garg et al. [10] provide a description of the transient identification technique.

LIGHT CURVE SIMULATIONS

Critical to resolving many of the discrepancies in the microlensing results is reducing non-microlensing contamination in the candidate sets. Selection criteria to reduce contamination, however, must be balanced against keeping detection efficiency high. This is particularly important as the underlying event rate for many of the contaminants, such as supernovae, can substantially exceed the rate of microlensing. Using simulations of both microlensing events and our most frequent contaminants, type Ia supernovae (SNeIa), we address the problem of non-zero contamination by determining quantitative estimates of the number of SNeIa passing the selection criteria.

A robust estimate of the detection efficiency and the contamination rate, however, requires a large number of simulations. Limitations on CPU time and disk space make simulations where fake "stars" are added to raw images and run through the reduction pipeline unfeasible. Instead, we simulate the light curves directly. Achieving simulations that accurately reflect the data, however, requires accurate models of the photometric uncertainties. The "shot-noise" contribution to the scatter is analytically modeled by Poisson statistics. Two other significant sources of uncertainty, however, must be determined empirically: (1) uncertainties introduced by an imperfect PSF model in the photometry package and (2) uncertainties introduced during the difference imaging process.

Systematic Uncertainties from the Photometry Package

To obtain SuperMACHO light curves we use a modified version of the DoPHOT package [11] to perform "forced difference flux photometry" [see 10]. To determine the amount by which DoPHOT underestimates the photometric error in each measurement, we create standard (non-differenced) light curves of bright, non-varying sources and determine the error-weighted mean magnitude. We then determine the size of the systematic uncertainty that must be added in quadrature to the photometric uncertainty for each measurement such that the square of the average error-weighted residual from the mean magnitude is one. Overall, we find that the typical value for the systematic error is 0.01 mag which we add in quadrature to the photometric uncertainties returned by DoPHOT.

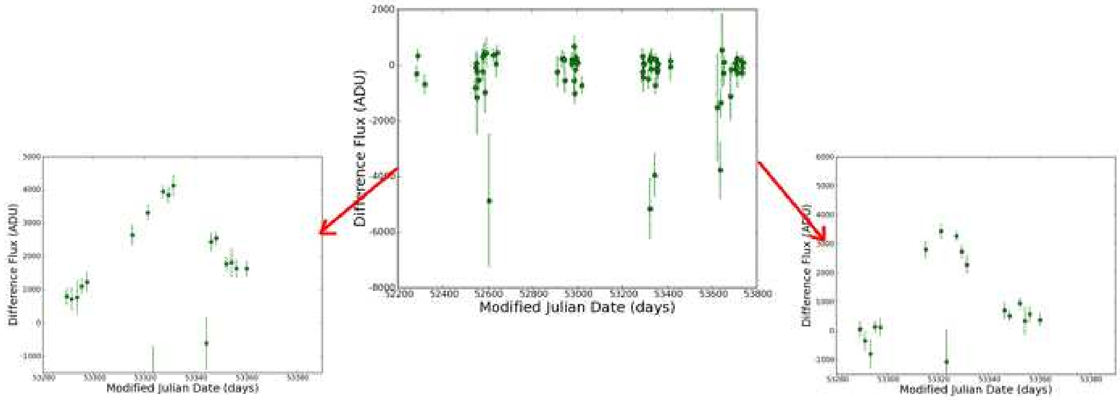

FIGURE 1. Direct difference flux light curve simulations. To exactly reproduce the excess scatter contributed by difference imaging in our simulations, we use the actual data. This figure shows a five year difference flux light curve (center). To this light curve we add a microlensing event (left) and a type Ia supernova (right) during the fourth season of observations. We show only the event year for the simulations. Note that both simulated light curves show the same excess noise and spurious low flux data points as the initial light curves. This methodology allows us to capture the noise and artifacts contributed by the difference imaging process.

Uncertainties From the Difference Imaging Process

While difference imaging provides an excellent technique for detecting small changes in source intensity, the process is also exposed to errors caused by slight changes in the background or observing conditions. As a result, difference flux light curves are plagued by errors and artifacts that are often spatially and temporally correlated. For example, poor seeing might cause flux from a non-varying, bright star to contaminate the light curves of fainter variable events surrounding it. Accurately modeling both the frequency and correlations in such errors is difficult. Instead, we use our actual data to reproduce this noise exactly in our simulations.

We accomplish this by generating a grid of $\sim 1.6 \cdot 10^6$ random positions distributed across our entire field-of-view. We obtain a difference flux light curve for each position. Because the majority of the surveyed area will not show any variability, these are nominally zero difference flux light curves that contain the additional scatter and artifacts contributed by the image differencing. To these light curves we then add simulated microlensing events and type Ia supernovae with the additional Poisson and 0.01 mag scatter [see 12]. Figure 1 shows simulations of a microlensing and type Ia supernova created from the same zero-flux light curve.

SELECTION CRITERIA

Using the simulated light curves, we develop and train a set of selection criteria that minimize SNeIa contamination while maximizing our microlensing detection efficiency.

To achieve this, we define a parameter space of light curve descriptors and map the distribution of simulated light curves within them. We then define selection criteria that target specific regions of this space [12]. Qualitatively, these criteria address four questions about each light curve:

1. Is this a *unique* event? Or does the variability repeat?
2. Is the event temporally *well-sampled*? Does it have sufficient *signal-to-noise*?
3. Is the variability *microlensing-like*?
4. Is the variability *unlike known contaminants* (e.g. supernovae, active galactic nuclei)?

Light curves passing all criteria are included in the final set of microlensing candidates. Our simulations also allow us to quantitatively estimate the number of type Ia supenovae that will remain as contaminants in the candidate set. Depending on the supernova rate we assume $10^{-4.5} yr^{-1} Mpc^{-3}$ or $10^{-4.2} yr^{-1} Mpc^{-3}$ [see 13], we expect between 6 and 12 SNeIa to pass these selection criteria. Assuming the microlensing rate and event parameter distribution observed by MACHO [1] and using the LMC luminosity functions described by Rest et al. [6], we expect 14 microlensing events to pass these selection criteria.

Overall, we find 20 candidates that pass these criteria. Some of these light curves, however, show activity indicative of non-microlensing variability. Because SuperMACHO probes deeper than previous surveys, we are more sensitive to extragalactic activity and the majority of our stars are in different stages of stellar evolution than in previous surveys. Though type Ia supernovae remain our dominant contaminant, we find that we must also target other sources of non-periodic stellar variability more directly. We are currently re-reducing the data to produce cleaner light curves and working toward improved selection criteria.

CONCLUSION

Interpretation of results from microlensing surveys of the Magellanic Clouds can be muddied by unknown levels of contamination. Simulations of both microlensing and common contaminants can provide quantitative estimates of both the detection efficiency and the equally important contamination rate. For SuperMACHO, the most significant source of contamination comes from SNeIa. Using simulations, we find that the number of SNeIa passing our criteria (6–12) may be comparable to the number of microlensing events (14). We also find that our selection criteria do not select against some classes of variables that occurred less frequently in previous surveys. This suggests a need to revise our selection criteria. We note, however, that any new selection criteria must also be determined in an unbiased manner that does not target specific candidate light curves. Instead we must model the underlying populations of variables present in the SuperMACHO data and develop our criteria accordingly.

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