The First Data from the MACHO Experiment*

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ABSTRACT

MAssive Compact Halo Objects such as brown dwarfs, Jupiters, and black holes are prime candidates to comprise the dark halo of our galaxy. Paczynski noted that objects (dubbed MACHOs) with masses in the range $10^{-6} M_\odot < M < 100 M_\odot$ can be detected via gravitational microlensing of stars in the Magellanic Clouds with the caveat that only about one in $10^6$ stars will be lensed at any given time. Our group has recently begun a search for microlensing using a refurbished 1.27 meter telescope at the Mount Stromlo Observatory in Australia. Since the summer of 1992, we have been imaging up to $10^7$ stars a night in the Large Magellanic Cloud using our large format two-color $3.4 \times 10^7$ pixel CCD camera. Here I report on our first results based on an analysis of $\sim 10^6$ of these stars. Although this is not enough data to make definitive statements about the nature of the dark matter, we are able to conclude that the rate of variable star background events is not larger than the expected MACHO signal.

1. Introduction

The nature of the dark matter which dominates the mass of galaxies is arguably the most important unsolved problem in astronomy. The most fashionable idea about the nature of this dark matter is that it is made up of exotic elementary particles such as WIMP’s or axions that have never been observed. The discovery of anisotropies in the Cosmic Microwave Background Radiation by the COBE-DMR team\(^1\) has been widely hailed by some prominent scientists and in the popular press as providing strong support for the idea that the dark matter is composed primarily of exotic elementary particles. In fact, although the COBE-DMR detection does provide strong support for the idea that the structure in the universe is a result of gravitational amplification of small initial perturbations, it does not support the simplest model based on exotic dark matter (the standard Cold Dark Matter model). The true state of affairs was revealed at the Cosmic Microwave Background Workshop held at LBL immediately prior to this meeting. After hearing numerous talks about models with “tilted spectra” and two types of exotic dark matter all contrived to fit the COBE data, the participants were asked to vote on which theory stood the best chance of being correct. The winner with an overwhelming plurality of the vote was a “baryons only” cosmology with no exotic dark matter, so the case for non-baryonic matter is apparently not as strong as many have been led to believe. In the remainder of this talk, I will argue that we will soon have a better way of determining the composition of the universe, as dark matter search experiments will soon be generating definitive constraints on the nature of the dark matter.

If the galactic dark matter is composed of baryons, then it cannot be made of normal stars, dust, or gas, which would readily be detected. Instead, it would have to be in the form of brown dwarfs, “Jupiters,” white dwarfs, neutron stars, or black hole stellar remnants. These objects can all be detected by the technique of gravitational microlensing, and have come to be known as MACHOs (for MAssive Compact Halo Objects).

Gravitational microlensing refers to lensing in the case where there is significant amplification of the source, but the lensing angle is too small to be observed. Paczynski\(^2,3\) has shown that the “optical depth” for microlensing by the dark halo of our galaxy is \(\sim 5 \times 10^{-7}\), so that at any given time about 1 star in \(2 \times 10^6\) will be microlensed with amplification by a factor of 1.34 or larger. (The typical angular separation of the images is \(\lesssim 0.001\) arc second, so they cannot be resolved.) The fundamental unit of length for a microlensing is the Einstein ring radius which is given by

\[
R = 2 \left( \frac{GMx(L - x)}{c^2L} \right)^{1/2}
\]

where \(L\) is the distance to the source star (in our case in the Magellanic Clouds) and \(x\) is the distance to the lensing object in the halo. If \(R\) is not too small, the source star can be assumed to be a point light source, and the microlensing amplification depends only on the dimensionless
impact parameter \( (u \equiv b/R) \):

\[
A(u) = \frac{u^2 + 2}{u\sqrt{u^2 + 4}}
\]

\( u = 1 \) corresponds to an amplification of 1.34. For source stars in the Magellanic clouds, the point-like approximation fails only when the mass of the lensing objects is less than \( M \lesssim 10^{-7}M_\odot \).

The time scale of a microlensing event is given by the timescale for the lensing object to traverse a distance equal to the impact parameter \( b \) which yields

\[
\Delta t = 7 \text{ days} \sqrt{\frac{M}{10^{-2}M_\odot}}
\]

for a typical lensing object located at a distance of 10 kpc moving at a velocity of 200 km/sec.

The microlensing light curve will be distinguishable from the background of variable stars in several important ways: they are achromatic, time-symmetric, and non-repeating. These signatures should allow us to distinguish most (and hopefully all) of the variable stars from the microlensing events. In addition, the microlensing light curve is described by just 3 parameters: the maximum amplification, the time of the maximum amplification and the duration of the event. A convincing microlensing signal would certainly require that at least some of the detected microlensing events have a very high amplification and a well sampled light curve.

2. The Macho Telescope System

The search for gravitational microlensing by Machos in the halo of our galaxy requires that we survey large numbers of stars in the Magellanic Clouds and/or Galactic Bulge on a nightly basis for several years. To accomplish this goal, we have obtained the recently refurbished Mt. Stromlo 50” “Great Melbourne Telescope” for four years of dedicated use. Since our survey requires a wide field of view, we have installed a system of corrector lenses (designed by E. H. Richardson and I.Z. Lewis) which give us a 1° diameter field of view and reduces the f ratio to f/3.88 (giving an image scale of 41 arcsec/mm). In addition, a dichroic filter within the corrector is used to split the beam into two channels (which we have chosen to be 4500A - 6300A, and 6300 - 7800A) to give simultaneous imaging in two colors.

In order to image these large fields of view, two large CCD cameras\(^4\) have been fabricated (for the “red” and the “blue” channels) each containing 2 x 2 mosaics of 2048 x 2048 CCDs, fabricated by Loral Aerospace. These CCDs have two readout amplifiers per chip and 15 micron pixels (\( \simeq 0.63” \) on the sky). Using all 16 readout amplifiers simultaneously, the CCDs are read out in about 70 seconds with a read noise of less than 10 electrons. For our typical exposure time of 300 seconds, we are able to take 8-9 exposures per hour, and we can generally take more than 60 images on a clear night in the middle of the LMC season.
3. Data Pipeline and Photometric Analysis

Since our cameras produce data at a prodigious rate, it is highly desirable to have a data pipeline that is both automatic and computationally efficient. Raw image data from the cameras passes down a fiber optic line to 128 MBytes of buffer memory on a VME Bus extension to a Sun Sparc IPC. The images are then written to magnetic disk and copied to tape. While the images are resident on disk, our 4-processor Solbourne reduces the data to photometric measurements using our custom built PSF fitting photometry routine, SoDOPHOT (originally based on DOPHOT\textsuperscript{5}). SoDOPHOT uses a template of positions and magnitudes from a good seeing image as a starting point for its fits, and we find that the photometry obtained with varying seeing and sky brightness is much more reproducible than with the standard versions of DOPHOT or DAOPHOT. The photometric output includes a number of parameters and flags designed to help identify possible photometric problems. The quantities output include the PSF fit $\chi^2$, measures of cosmic ray contamination and the fraction of the PSF that is lost to bad pixels, and a seeing-dependent crowding estimator.

Although we have established that our photometric analysis system can easily keep up with the incoming data, the software to control the automated photometric reduction of all our data is not yet fully operacional. The results reported below are based on an analysis of about 15\% of our data generated by running SoDOPHOT outside our automatic analysis pipeline.

4. First Results

As of the end of November, 1992, we have analyzed 182 images of 3 fields in the LMC bar. The total number of stars contained in these fields is about 1.2 million, and the total number of two-color photometric measurements in this data set is about 72 million. (By the end of January, 1993, we had analyzed 419 images of 5 LMC bar fields containing 1.7 million stars.) In every image we take, our photometry routine, SoDOPHOT, makes photometric measurements for all the stars in that image, even those stars whose signal is below the noise in the image being reduced. (The stellar content and relative positions had previously been determined from the high quality “template image”.) Thus, when the seeing is poor or the sky is bright, the photometric errors can become large. About 50\% of these measurements have errors of less than 15\%.

We have performed a preliminary time series analysis on this data to search for variable stars and possible MACHO events. We have set up cuts on a number of the SoDOPHOT output parameters in order to remove suspect data. Variable star candidates are determined by selecting stars which are not a good fit to a constant light curve. This can be done on the full data set or a “robust” set in which the measurements with the largest deviations from the mean have been removed. This procedure has yielded several thousand variable candidates. Periods for some of these variables have been determined using the phase dispersion minimization method of Stellinwerf. A few of these light curves for short period variables are plotted in Fig. 1.
Figure 1: Two color light curves for 2 short period variables.

Although we rarely image the same field more than twice a night, we are able to obtain good light curves for these stars because there is sufficient randomness in our observing schedule.

The results of our preliminary microlensing searches have been quite encouraging. We flag microlensing candidates using optimal filters of several different durations, and do a simultaneous microlensing curve fit in both colors for the candidates which passed the filters. The candidate list generated from more than a million light curves is easily reduced to a handful
of stars by cutting out stars which are a poor fit to the microlensing light curve, have very poor sampling or low signal to noise near the peak, or are flagged by the SoDOPHOT output parameters as having potential photometry problems. The result of this procedure is that, we have no good microlensing candidates when a preliminary estimate of our detection efficiency suggests that we should have seen 1 or 2 strong events. Fig. 2 shows a light curve of one of our “close calls” (star 29-3902 in field 79). While the $\chi^2$ value for the 2-color microlens curve fit indicates an acceptable fit, closer inspection indicates that light curve is actually a poor fit near the peak. The 17 data points within 18 days of the peak have a $\chi^2 = 32.4$ for (essentially) 14 degrees of freedom, so we can exclude microlensing at better than the 99% confidence level. We do have a couple of other events that are consistent with microlensing, but their signal-to-noise is too low to claim a detection.

**Figure 2:** The two-color light curve of a “near” MACHO-candidate plotted in linear units. The unamplified magnitudes ($A = 1$) correspond to $MR = 16.83$ and $MV = 17.02$. These light curves are not well fit by a microlensing light curve near the peak.

Our conclusion from this preliminary analysis is that while we have not analyzed enough data to put a statistically significant limit of the abundance of MACHOs in the Halo of our
galaxy, this analysis has clearly demonstrated that the background of variable stars mimicing microlensing events is at worst comparable to our expected signal. Since we have not yet used all the tools at our disposal for rejecting background events (such as location on the Color-Magnitude diagram or the spectra of candidate stars), we believe that the variable star background will not seriously hinder our efforts to confirm or deny the existence of MACHOs.

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