MACHO COLLABORATION SEARCH FOR BARYONIC DARK MATTER VIA GRAVITATIONAL MICROLENSING

K. Griest[*,†], C. Alcock[‖,†], R.A. Allsman[‖], T.S. Axelrod[‡], D.P. Bennett[†,‖],
K.H. Cook[‖,†], K.C. Freeman[‡], J. Guern[*,†] M. Lehner[*,†], S.L. Marshall[†,♭],
S. Perlmutter[†], B.A. Peterson[‡], M.R. Pratt[†,♭], P.J. Quinn[‡],
A.W. Rodgers[‡], C.W. Stubbs[†,♣], W. Sutherland[♠], D. Welch[♡]
(The MACHO Collaboration)

[*] *Department of Physics, University of California, San Diego, CA 92039*
[†] Center for Particle Astrophysics, University of California, Berkeley, CA 94720
[‖] *Lawrence Livermore National Laboratory, Livermore, CA 94550*
[‡] *Mt. Stromlo and Siding Spring Observatories,*
Australian National University, Weston, ACT 2611, Australia
[♭] *Department of Physics, University of California, Santa Barbara, CA 93106*
[♣] *Department of Astronomy, University of Washington, Seattle, WA 98195*
[♠] *Department of Physics, University of Oxford, Oxford OX1 3RH, U.K.*
[♡] *Department of Physics and Astronomy, McMaster University,*
Hamilton, ON L8S 4M1, Canada

I present results from the MACHO collaboration gravitational microlensing search. I describe the experiment and the nearly 50 microlensing events that have been detected. Limits on the baryonic content of the halo are given, as are estimates of the Macho contribution to the dark halo. Optical depths toward the bulge, and several unusual events such as a binary lens and a parallax event are discussed. Possible interpretations of these results are also discussed.

1. Introduction

It is remarkable that science can discover exotic states of matter such as the top quark, and detect one part in 10^5 fluctuations in the microwave background and still not know what the primary constituent of the Universe is. Over the past decades the existence of this mysterious dark matter has become accepted, as evidence for its gravitational dominance has become overwhelming. It is "seen" on scales from small dwarf galaxies, to large spiral galaxies like our own, to clusters of galaxies, to the largest scales yet observed. The best evidence for dark matter comes from the rotation curves of spiral galaxies like our own Milky Way. Using 21 cm emission to detect neutral hydrogen far beyond the visible edge of galaxies, it is clear that 3 to 10 times as much dark matter as visible matter must exist in these systems. Translating these results into Ω, the density averaged over the Universe

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[⋆] To appear in the proceedings of the Pascos/Hopkins Symposium, Baltimore, Maryland, World Scientific, 1995 divided by the critical density, one finds $\Omega_{halos} >\sim 0.03$. On larger scales, such as in clusters or from large scale flows, larger amounts of dark matter are found (for example, $\Omega > 0.2$), but the results are less robust.[1,2] When compared with density of luminous matter, $0.003 < \Omega_{lum} < 0.008$, the extent of the dark matter problem becomes clear.

One would like to know what this dark material is, but how does one detect something that neither emits nor absorbs electromagnetic radiation at any known wavelength? If the dark matter consists of exotic elementary particles such as Wimps[3] or axions,[4] then the only way is via particle accelerators or special purpose laboratory experiments. However, if the dark matter consists of astronomical objects in the $10^{-8}\mathrm{M}_\odot$ to $10^{3}\mathrm{M}_\odot$ range, then the 1986 idea of Paczyński[5] of using gravitational microlensing can be applied. Now constraints from big bang nucleosynthesis imply that if $\Omega_{tot} = 1$, then most of the dark matter must be non-baryonic; that is, consist of exotic elementary particles. However, as seen from the numbers above, all the dark matter in the halos of spiral galaxies could be baryonic and still satisfy the nucleosynthesis constraint $0.01 < \Omega_{baryon} < 0.1$. Since all dark matter detection experiments, including the searches for Wimps and axions, search only for dark matter in the Milky Way halo, and since it is the spiral galaxy halo dark matter which is by far the most secure, it should be clear that a search for baryonic dark matter is essential. Candidate baryonic objects include brown dwarf stars, jupiter mass objects, or remnants from an early generation of star formation; basically any astronomical objects which would now be too small or too dim to be seen at large distances. The remarkable thing about microlensing experiments is that they are sensitive to all such objects over a huge range of masses.

There are now several groups, including our own, which are returning results from searches for baryonic dark matter, and it is these results which I want to discuss. While it is now clear that we have not discovered enough dark matter to make up a full standard dark halo, we seem to have discovered a substantial new component of our galaxy, and may well have found a part of the long-sought dark matter.

2. Microlensing

In order to explain the roughly flat rotation curve of the Milky Way, a large dark halo, usually spherical, extending to at least 50 kpc is hypothesized. The density of this halo should drop roughly as r^{-2} at large radii to produce a flat rotation curve, and the objects making up this halo should move with velocities in the 270 km/sec range in order to satisfy hydrostatic equilibrium. This is true whether the objects are elementary particles or massive compact halo objects (Machos).

The idea of microlensing rests upon Einstein's observation that if a massive object lies directly on the line-of-sight to a much more distance star, the light from the star will be lensed and form a ring around the lens. This "Einstein ring" sets the scale for all the microlensing searches, and in the lens plane, the radius of that ring is given by

$$r_E = 610 R_\odot [\frac{m}{\mathrm{M}_\odot} \frac{L}{\mathrm{kpc}} x(1-x)]^{1/2},$$

where $R_\odot$ and $\mathrm{M}_\odot$ are the solar radius and mass, m is the Macho mass, L is the distance to the star being monitored, and x is the distance to the Macho divided by L.

In fact, it is extremely unlikely for a Macho to come precisely on the line-of-sight, but if there is a near miss, two images of the star appear separated by a small angle. For masses in the stellar range and distances of galactic scale this angle is too small to be resolved, but the light from both images add and the star appears to brighten. The amount of brightening can be large, since it is roughly inversely proportional to the minimum impact parameter b/r_E. Since the Macho, Earth, and source star are all in relative motion, the star appears to brighten, reaches a peak brightness, and then fades back to its usual magnitude. The brightening as a function of time is called the "lightcurve" and is given by

$$A(u) = \frac{u^2+2}{u\sqrt{u^2+4}}, \qquad u(t) = [u_{min}^2 + (2(t-t_0)/\hat{t})^2]^{1/2},$$

where A is the magnification, $u = b/r_E$ is dimensionless impact parameter, t_0 is the time of peak amplification, $\hat{t} = 2r_E/v_\perp$ is the duration of the microlensing event, $v_\perp$ is the transverse speed of the Macho relative to the line-of-sight, and u_{min} is value of u when $A = A_{max}$. Thus the signature for a microlensing event is a time-symmetric brightening of a star occurring as a Macho passes close to the line-of-sight. When a microlensing event is detected, one fits the lightcurve and extracts A_{max}, t_0, and $\hat{t}$. The primary physical information comes from $\hat{t}$, which contains the Macho velocity, and through r_E the Macho mass and distance. Unfortunately, one cannot uniquely find all three pieces of information from the measurement of $\hat{t}$. However, statistically, one can use information about the halo density and velocity distribution, along with the distribution of measured event durations to gain information about the Macho masses. Using a standard model of the dark halo, Machos of jupiter mass ($10^{-3}\mathrm{M}_\odot$) typically last 3 days, while brown dwarf mass Machos ($0.1\mathrm{M}_\odot$) cause events which last about a month.

In order to perform the experiment, a large number of stars must be followed, since, assuming a halo made entirely of Machos, the probability of any Macho crossing in front of a star is about 10^{-6}. Thus many millions of stars must be monitored in order to see a handful of microlensing events. In addition, if one wants to see microlensing from objects in the dark halo, the monitored stars must be far enough away so that there is a lot of halo material between us and the stars. Therefore, the best stars to monitor are those in the Large and Small Magellanic Clouds (LMC and SMC) at distances of 50 kpc, and 60 kpc respectively, and also stars in the galactic bulge, at 8.5 kpc.

There are several experimental groups that have undertaken the search for microlensing in the LMC and galactic bulge and have returned results. The EROS collaboration, has reported 3 events towards the LMC[6], the OGLE group has reported about 15 events towards the bulge,[7] and the DUO collaboration has about a dozen preliminary events towards the bulge.[8] Our collaboration has seen about 5 events towards the LMC,[9,10,11] and about 50 events towards the bulge.[12,13,14] We are also monitoring the SMC, but have yet to analyze that data. In what follows I will concentrate on MACHO collaboration data.

3. MACHO Experiment

The MACHO project has full-time use of the 1.27-meter telescope at Mount Stromlo Observatory, Australia, for a period of at least 4 years from July 1992. In order to maximize throughput a dichroic beamsplitter and filters provide simultaneous images in two passbands, a 'red' band (approx. 5900–7800 Å) and a 'blue' band (approx. 4500–5900 Å). Two very large CCD cameras[15] are employed at the two foci; each contains a 2 × 2 mosaic of 2048 × 2048 pixel Loral CCD imagers, giving us a sky coverage of 0.5 square degrees. Observations are obtained during all clear nights and part nights, except for occasional gaps for telescope maintenance. The default exposure times are 300 seconds for LMC images, 600 sec for the SMC and 150 seconds for the bulge, so over 60 exposures are taken per clear night. As of 1995 April, over 30000 exposures have been taken with the system, of which about 19000 are of the LMC, 2000 of the SMC and 9000 of the bulge. The images are taken at standard sky positions, of which we have defined 82 in the LMC, 21 in the SMC and 75 in the bulge.

Photometric measurements from these images are made with a special-purpose code known as SoDoPHOT,[16] derived from DoPHOT[17]. For each star, the estimated magnitude and error are determined, along with 6 other parameters (quality flags) measuring, for example, the crowding, and the χ^2 of the point-spread-function fit. It takes about an hour on a Sparc-10 to process a field with 500,000 stars, and so with the computer equipment available to us we manage to keep up. The set of photometric datapoints for each field are re-arranged into a time-series for each star, combined with other relevant information including the seeing and sky brightness, and then passed to an automated analysis to search for variable stars and microlensing candidates. The total amount of data collected to date is more than two Terabytes, but the time-series database used for analysis is substantially smaller.

4. Event Selection

Most of the stars we monitor are constant within our photometric errors, but about one half of one percent are variable. The MACHO database, as repository for the largest survey ever undertaken in the time domain, is an extremely valuable resource for studies of variable stars. From our first year LMC data alone we have already identified about 1500 Cepheid variables, 8000 RR Lyrae, 2200 eclipsing binaries, and 19000 long period variables. Example lightcurves from each of these classes are shown in Figure 1. We also have many rare variables, and have given the first conclusive evidence of 1st overtone pulsation in classical Cepheid's[18] We have also observed what may turn out to be entirely new types of variable stars.[19]

Given that the incidence of stellar variability, systematic error, and other sources of stellar brightening is much higher than the incidence of microlensing, how can one hope to discriminate the signal from the background among the tens of millions of stars we monitor nightly? Fortunately, there are several very powerful microlensing signatures which exist:

1. High amplification. Very high amplifications are possible, so we can set our

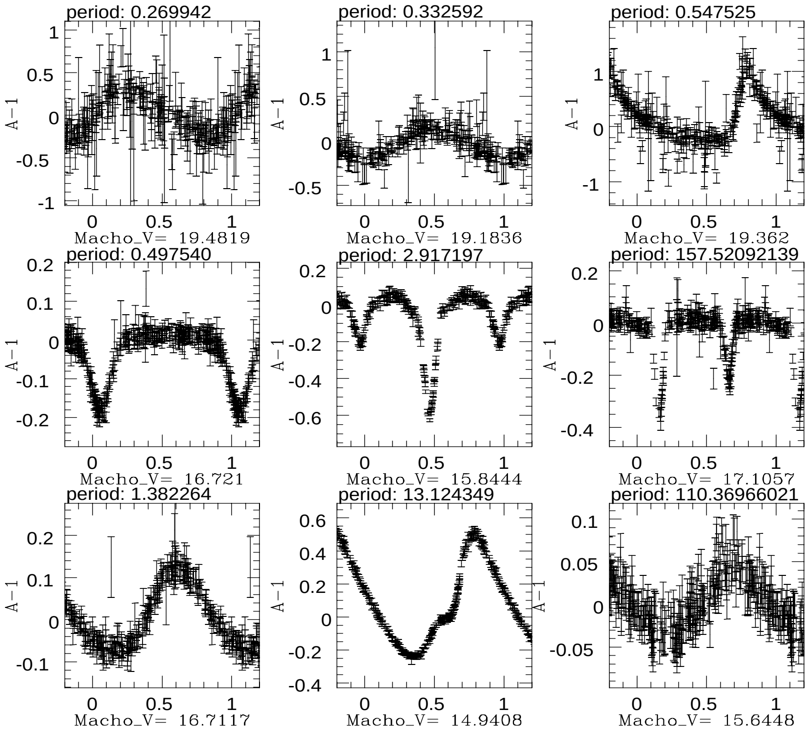

Figure 1. Example phased variable star lightcurves from first year LMC data. The top row shows RR Lyrae variables of type RRe, RRc, and RRab. The second row shows a range of periods for eclipsing binaries. The third row shows an overtone and a fundamental mode Cepheid and a low amplitude Long Period Variable.

A_{max} threshold high enough to avoid many types of systematic error background.

2.) Unique shape of lightcurve. Only 5 parameters are needed to completely specify the 2-color lightcurve.

3.) Achromaticity. Lensing magnification should be equal at all wavelengths, unlike brightenings caused by most types of stellar variability.

4.) Microlensing is rare. The chance of two microlensing events occurring on the same star is so small, that any star with more than one “event” can be rejected as a microlensing candidate.

5.) Statistical tests: The distribution of peak magnifications A_{max} is known a priori. Microlensing should occur with equal liklihood on every type and luminosity of star, unlike known types of stellar variability. New microlensing events should be discovered each year at a constant rate.

6.) Alert possibility. Our alert system is now working and we can catch microlensing before the peak and get many measurements of high accuracy. Other spectral and achromaticity tests can also be performed in follow-up mode.

Using these criteria, as well as others, we have found it possible to pick out microlensing candidates from variable stars, etc. For example, starting with about

9.5 million lightcurves from our first year LMC database, we remove all but 40000 by requiring a significant bump in both the red and blue lightcurves, and removing the reddest 0.5% of stars (which are mostly long period variables). Then performing a microlensing fit, and making cuts on statistics such as the χ^2 per degree of freedom of the fit, the "crowding" of the star, the number of points in the peak, and the duration of the event, etc. we reduce the number of candidates down to a few thousand. Our last two cuts are made on the maximum magnification and the improvement in fit χ^2 when a microlensing fit is compared to a fit to a constant star. We are left with a handful of events. Several of these are nebulosity junk, long time scale bumps on faint stars in the middle of high nebulosity regions. For our efficiency calculation, an automated way of removing such events was developed. Two of the remaining events are in fact the same star which happened to reside in a field overlap. So we are left with three microlensing candidates. These are shown in Figure 2.