

All About MACHO

by KIM GRIEST

*A group of astronomers
and physicists discover
the gravitational
microlensing effect
and make a major
contribution to particle
physics.*

WITH ALL THE RECENT SCIENTIFIC and technological progress it is remarkable that we still don't know what is the most common physical substance in the Universe. This mysterious "dark matter" completely dominates the gravity of all systems that have been measured; it controls the motion of the Sun through the Galaxy, the motion of galaxies in clusters of galaxies, and the formation and fate of all structure in the Universe. But we don't have a clue what this stuff is. We know that there is 10-30 times more of it than there is in ordinary stars, dust, or gas, and we even know that it is distributed in large halos surrounding all galaxies, and how fast it is moving. But as for its nature we only know that it doesn't emit or absorb much electromagnetic radiation in any known waveband. So what could it be, and how can we go about identifying it?

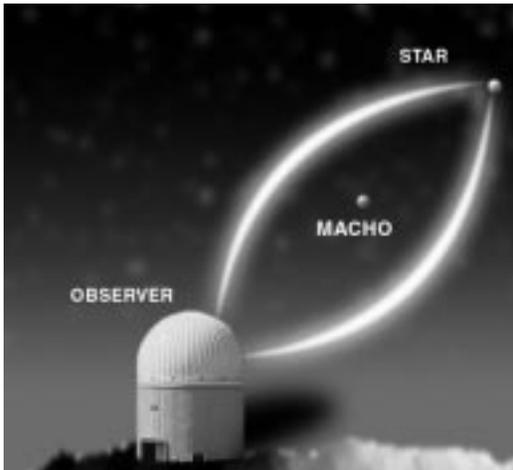
This article will give a short overview of how we know dark matter exists and what the main candidates are. Then it will focus on one of the most popular candidates, Massive Astrophysical Compact Halo Objects (MACHOs), which has been the subject of an extensive search among astronomers. After the discovery of MACHOs in 1993, some thought that the dark matter puzzle had been solved, but theoretical work, as well as very recent experimental results, show that while a portion of the dark matter may consist of MACHOs, the bulk of it must be some other, still mysterious, stuff.

DARK MATTER is seen in many places, but the most secure evidence comes from the speeds of stars and hydrogen gas clouds moving in spiral galaxies. These speeds, accurately measured using the Doppler effect, are much faster than can be explained if only the gravity from observed stars, gas, and dust is taken into account. Especially in the outer reaches of spiral galaxies, where there are very few stars, the high speeds imply 5–10 times more material than observed. In order to explain the high speeds, this “dark matter” must be distributed in large roundish halos surrounding the stellar component of spiral galaxies. This is true of basically every spiral galaxy measured, including our own Milky Way.

On scales larger than galaxies, even more dark matter is required to explain the speeds of objects. For example, in large clusters of more than a thousand galaxies, the speeds of those galaxies imply a mass of dark matter that is 10–30 times greater than that of visible stars and gas. In these systems there are other ways to measure the depth of the gravitational potential well, for example from the X-ray temperature of the free hot gas or from the gravitational lensing of background galaxies. These independent methods give the same large amount of dark matter as inferred from the high speeds of the cluster galaxies. Thus, there is no controversy about the existence of large amounts of dark matter.

WHAT TYPES OF OBJECTS could make up the enormous amount of dark matter, and how does one search for something that is invisible in all known electromagnetic wavebands?

For years astronomers have known of many types of objects that could fit the dark matter invisibility requirement: black holes, Jupiter-size balls of hydrogen and helium, white dwarf stars, neutron stars, and so forth. But for decades, astronomers were at a loss for how to search for such objects, none



Light from the star can reach the observer by two different paths, making a double image. The paths are enormously exaggerated above, and usually the atmosphere blurs the two images into one, but in any case more light than normal is seen coming from the star.

of which give off enough light to be seen at the typical distance of a dark matter object. Particle physicists, however, were more enthusiastic about the prospects of detecting their dark matter candidates. It is quite natural that some type of exotic, weakly interacting elementary particle would be left over from the Big Bang with an abundance appropriate to make up the dark matter. The two most popular classes of candidates are the axion and the Weakly Interacting Massive Particle (WIMP) class, the most popular of which is the neutralino from supersymmetry. Axions would exist with the proper density to be the dark matter if they had masses near 10^{-5} eV, while WIMPs could contribute the bulk of the dark matter with masses in the tens to thousands of GeV range. The advantage of particle dark matter for detection is that each second billions of them would be passing through each square centimeter of the entire Galaxy, including all areas of the Earth. The predicted tiny cross section makes detection difficult, but many experimental efforts are underway to detect axions or WIMPs by using very low noise, carefully instrumented detectors. Of course for supersymmetric WIMPs it may also be possible to create directly the particles in an accelerator, and then to use the measured mass and cross section to predict the contribution to the dark matter. This search is also underway. So far, however, no conclusive evidence in favor of any dark matter particle has been found.

For the astronomical candidates MACHOs, the situation changed in 1986 when Bodhan Paczynski suggested a method of detecting any

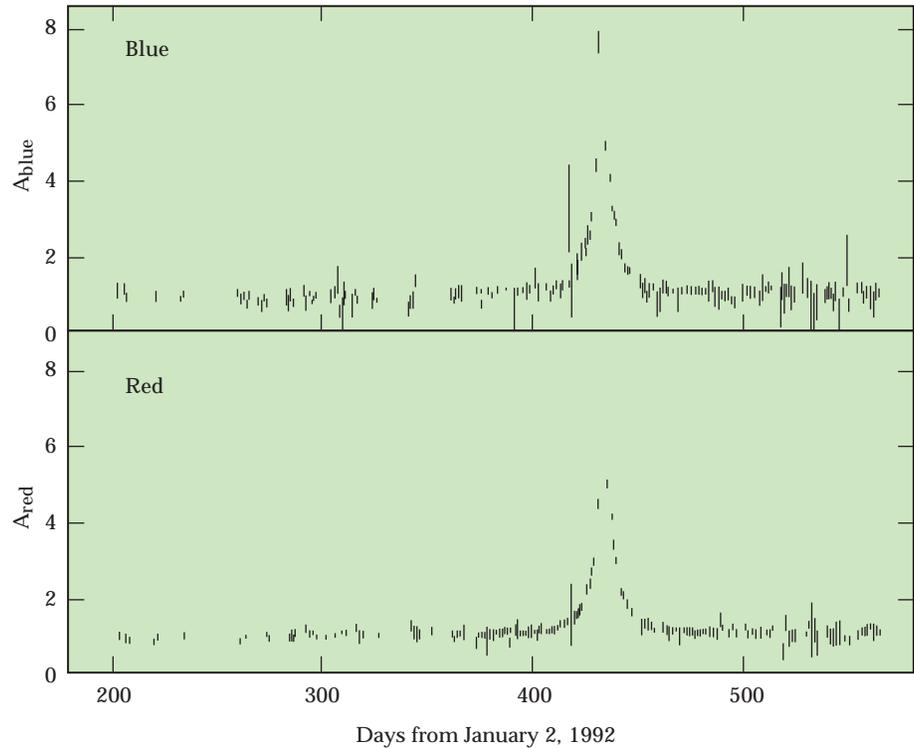
compact object that might make up the dark matter in our Galaxy. Starting in 1989, this idea gave rise to several experiments, culminating in 1993 with their discovery!

GRAVITATIONAL microlensing is the method capable of detecting the presence of dark objects in the Galaxy at great distance. This idea, studied even by Albert Einstein, says that if a dark object moves directly in front of a distant source star, the source star will appear to be magnified by the dark object acting as a gravitational lens (see the illustration on the left). If the alignment is perfect, the source would in fact appear as a ring, called the Einstein ring, with radius $R_E = [4GmLx(1-x)/c^2]^{1/2}$, where G is Newton's constant, m is the mass of the lens, L is the distance to the source star, and x is the distance to the lens divided by the distance to the source. In the much more likely case of imperfect alignment, for example, missing perfect alignment by an impact parameter b , there will be two images of the source instead of a ring. For distances and masses typical of microlensing experiments, these images will be too close together to be resolved, but the light from them will add, giving a total magnification of the source star by a factor $A = (u^2+2)u^{-1}(u^2+4)^{-1/2}$, where $u = b/R_E$.

Thus the idea is to monitor many stars in a nearby galaxy, such as the Large Magellanic Cloud (cover image), and see if any of them become magnified as a dark matter MACHO passes in front. If the halo of the Milky Way consists of MACHOS (and not WIMPs or axions), then there

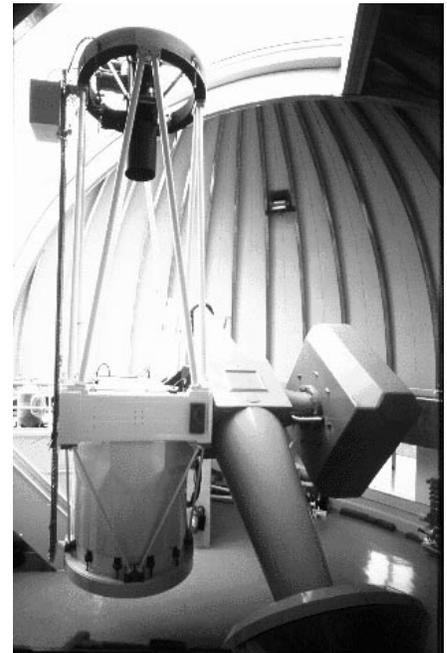
should be trillions of MACHOs moving at speeds near 300 km/sec through the halo. As the Earth, source star, and MACHO move into and out of alignment, the source star appears to brighten, then goes back to its normal brightness, in a time-symmetric and very specific unique way. One can calculate the probability of a MACHO passing in front of a star and also the typical duration of the magnification event. One finds that for a full MACHO halo, about one star in two million will be magnified and that the duration of the event ($A > 1.34$) will be $\hat{t} \approx 130 (m/M_{\odot})^{1/2}$ days, where m/M_{\odot} is the mass of the MACHO in units of solar masses. Thus if one monitored millions of stars over a period of several years, one could in principle detect MACHO dark matter. If one did not see any microlensing events, one could also rule them out as dark matter candidates. Since one can monitor stars on times scales of minutes to years, this type of experiment has sensitivity to any compact dark matter objects in the $10^{-7} M_{\odot}$ to $10 M_{\odot}$ range.

IN 1989 two experiments started with the purpose of monitoring millions of stars for microlensing to detect dark matter. The EROS collaboration, consisting mostly of French astrophysicists and particle physicists, used a telescope in South America, while the MACHO collaboration of American and Australian scientists used a telescope in Australia. I will focus on the MACHO collaboration, since I am a member of it. In addition, OGLE, a Polish collaboration, began monitoring stars for microlensing in the Galactic bulge for non-dark matter purposes.

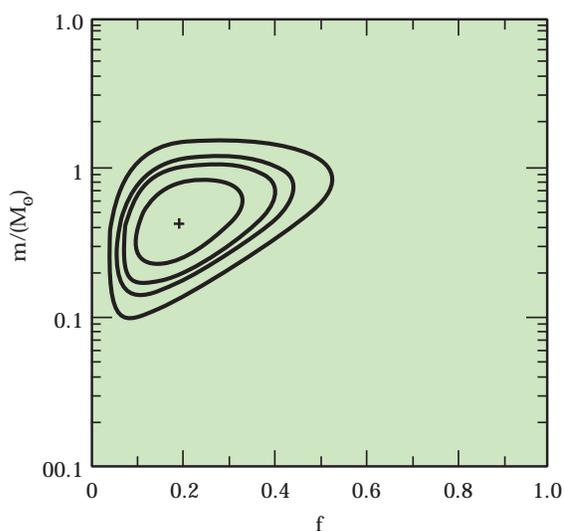


The MACHO collaboration used the 1.3 meter telescope at Mount Stromlo Observatory for eight years, 1992–1999. We took over 80,000 observations, recording more than 6 terabytes of raw image data, and made over 300 billion individual photometric measurements (of the brightness of a star). These measurements were arranged by date into more than 40 million stellar “light curves,” which were then each searched for signs of variability and gravitational microlensing. Most of the stars showed no sign of variability, but about 1 percent did vary, almost always in a way known to astronomers from their extensive studies of variable stars. These variable stars constitute background, but luckily the brightness variation due to microlensing is unique in its light curve shape. Thus it is possible to pick out the one-in-a-million light curve that contains a gravitational microlensing event. In 1993, the first such event was announced (see above illustration), and in 1997 a complete analysis of six events was finished. More recently, the MACHO collaboration has finished analysis of five-and-a-

A microlensing event discovered by the MACHO collaboration in 1993. Brightness of the star is plotted against time in two different band passes.



The 1.3 meter “Great Melbourne” telescope at Mt. Stromlo, Australia, used by the MACHO collaboration.



Results of recent microlensing analysis. Likelihood contours for the dark matter halo fraction f and the MACHO mass m . Contours are at confidence levels of 99 percent, 90 percent, and 68 percent. The most likely value is marked with a +, a halo made up of 20 percent MACHOs, with masses of $0.4 M_{\odot}$.

half years of data containing 14–17 microlensing events, and has given the best analysis to date. The EROS collaboration has also recently announced limits on the amount of MACHO dark matter.

TURNING the observed microlensing events into the fraction of dark matter that consists of MACHOs is not an easy task. First one must worry about contamination from variable stars and background supernova. For example, early analyses counted supernovas as potential microlensing. However, by checking the light curve shape, and by searching for the background galaxies associated with supernovas, this background can be removed, and it is expected that there is very little supernova contamination in the most recent microlensing samples. There are also types of variable stars (nicknamed “bumpers”) that have a constant brightness for a long time, then brighten for a short time in a time-symmetric way, quite similar to microlensing. These, however seem to occur only in stars of a specific brightness and color (as expected for a new type of variable star) and therefore can be eliminated as background. Microlensing is expected to occur randomly on stars of every type, color, and brightness.

Next, it is not an easy task to calibrate the experiment. There are rainy days, telescope glitches, bad seeing, full moons, and so forth which mean that the experiment is not equally sensitive to all the microlensing that occurs. In addition, the sampling of each star is not constant, and light curves that are assumed to consist of the light from one star,

may in fact be “blends” of several stars that happen to be near each other on the sky. As the quality of the atmosphere changes, the amount of blending will vary with time, giving unequal quality brightness measurements. Thus, it is a major task to understand how many microlensing events one would expect to see, even if the Milky Way halo consisted entirely of MACHOs. A major effort involving creation of artificial images under different conditions and Monte Carlo of the effects of all the above errors was undertaken, and the efficiency of the experiment calculated. This efficiency ranges from around 10 percent for events that last 10 days, to 50 percent for events of duration 200 days, to below 5 percent for events of duration 1000 days. Using this efficiency curve, one can do a proper comparison of the number of microlensing events expected and the number of microlensing events observed.

The result of this comparison is the likelihood plot shown in the illustration on the left. One sees that if the 14–17 microlensing events observed in the recent data set are all due to lensing of MACHOs, they represent about 20 percent of the dark matter in the Milky Way halo. Including Poisson uncertainties, the 95 percent confidence level for halo fraction is between 8 percent and 50 percent for a typical halo model. The mass of the MACHOs can also be estimated and is found to be between $0.15 M_{\odot}$ and $0.9 M_{\odot}$. Note that all the observed Large Magellanic Cloud microlensing events have durations longer than 20 days and that the non-observation of short duration events allows objects in the range $10^{-2} M_{\odot}$ to

$10^{-7}M_{\odot}$ to be ruled out as the dark matter. This is a very powerful result.

Micro-lensing aficionados usually quote results using the “optical depth” to micro-lensing. This is the probability that a given star is undergoing micro-lensing at any given time. A full MACHO halo predicts an optical depth towards the Large Magellanic Cloud of about 5×10^{-7} . The result of the above analysis gives a measured optical depth of 1.2×10^{-7} , quite consistent with the likelihood analysis.

The EROS collaboration has also recently reported the results of their analysis. They report two micro-lensing events and interpret their results as a limit on the amount of MACHO dark matter. They rule out a 50 percent MACHO halo at the 95 percent confidence level for MACHOs of masses under $0.4 M_{\odot}$.

IT SEEMS that while a portion of the dark matter may consist of MACHOs, the bulk of it cannot. Thus, the need to search for particle dark matter becomes more important than ever. Even before the micro-lensing results one had good theoretical reasons, based on Big Bang nucleosynthesis, to expect a large amount of non-baryonic dark matter. With the micro-lensing results, it becomes clear that even the dark matter in the halo of the Milky Way must consist mostly of some quite exotic material, such as a new type of elementary particle.

We also note that the measurement that 20 percent of the Milky Way dark matter consists of MACHOs requires several caveats. For example, it has been suggested that the Large Magellanic Cloud itself con-

tains a large extended population of faint stars. Such objects have not been detected, but also have not been ruled out. If they exist, the micro-lensing observed by the experiments may be due to “Large Magellanic Cloud self-lensing” rather than MACHOs moving in the dark halo of the Milky Way. Thus, in fact, the MACHO contribution to the Milky Way dark matter may be zero! However, this question has not been settled, and at this point a 20 percent MACHO halo is a reasonable hypothesis.

How will this question be settled? A main problem in current micro-lensing experiments is that they are incapable of determining the distance of the lens object. If Large Magellanic Cloud self-lensing is responsible for the observed micro-lensing events, then the lenses should all be at about 50 kpc, the distance of the Large Magellanic Cloud. If halo MACHOs are responsible, the typical lens distance should be around 10 kpc. Thus even a few determinations of lens distances would solve the problem. Fortunately there are several ways that new micro-lensing experiments could determine these distances. For example, the Space Interferometry Mission is capable of measuring the parallax of the lens and obtaining the lens distance. Other satellite or ground-based monitoring efforts may be able to determine parallaxes for certain classes of micro-lensing events. In addition, a certain fraction of micro-lensing events are “exotic” in that the light curve shape is modified by effects such as a binary lens, or the finite size of the source star. In such cases, it is sometimes possible to determine the lens distance.

One such binary event was seen towards the Small Magellanic Cloud (SMC), and the lens was determined not to be a member of the dark halo, but to be a SMC star lensing another SMC star. The Small Magellanic Cloud is known to be quite extended along the line-of-sight, so it was not surprising that the one measured event was SMC self-lensing. However, even one such event towards the Large Magellanic Cloud, which is not known to be extended, would be most valuable in settling the question of where the Large Magellanic Cloud lenses are located.

OF ALL THE SEARCHES for dark matter, the micro-lensing experiments have been the most powerful. They have detected what may be a significant portion of the dark matter, but perhaps as important, they have eliminated the main baryonic dark matter candidate as the primary constituent of the dark matter. Since all the main remaining candidates are exotic particles, it could be said that the micro-lensing experiments have given us one of the most important particle physics results in recent years! There are still puzzles to be solved concerning the nature of the discovered micro-lensing events, but several paths towards the solution of these puzzles are being pursued. We expect the answers in the near future.

