Looking for Dark Matter Through a Gravitational Lens: A Next Generation Microlensing Survey

Christopher W. Stubbs, University of Washington

Abstract

Among the most profound questions confronting physical scientists are the nature and distribution of "dark matter". This mysterious substance dominates the mass of galaxies such as the Milky Way, but does not emit or absorb detectable amounts of light. Its existence is inferred from determinations of galactic masses using the orbits of stars and gas. On a grander scale, whether the expansion of the Universe will continue forever, or will eventually reverse direction depends upon the overall cosmic density of dark matter. The fact that dark matter candidates range from exotic elementary particles to non-luminous astrophysical objects is evidence for how little we know about this hidden sector of the Universe.

I am engaged in an ambitious project that is searching for evidence of dark matter in the form of astrophysical objects, using the technique of gravitational microlensing. If the extensive dark matter halo of our Galaxy is made of such objects, then occasionally one of them will pass very close to the line of sight between the Earth and a distant star. The gravitational attraction of the dark object will deflect the light from the star, acting as a gravitational lens. This produces a transient brightening of the star, with a very characteristic signature.

Our team has carried out one of the most ambitious observing programs to date in optical astronomy, measuring nightly the brightness of tens of millions of stars over many years. After sifting through this vast sea of data, we have found a handful of microlensing events that could be the first hint of the detection of the dark matter of the Milky Way.

We need to determine whether the signal we are seeing is the result of lensing by dark matter objects, or by ordinary stars in unexpected places. In order to make a conclusive distinction between these alternatives we need at least a tenfold increase in the rate of detected events. This is readily achievable with a next-generation survey, conducted from a superior astronomical site, using state-of-the-art instrument and telescope technology.

A next-generation microlensing survey is being assembled by a capable and experienced team, with the objective of ascertaining the whether the Galactic dark matter has in fact been found.

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A Essay for the James S. McDonnell Foundation

Professor Christopher W. Stubbs

Department of Physics
and
Department of Astronomy
University of Washington
Seattle WA
USA.

A Golden Age

It comes as something of a surprise that the luminous stars and gas that we can see and photograph are, in fact, the minority component of a typical galaxy. We now know that the beautiful textbook photographs of spiral galaxies are not accurate renditions. Most of the galaxy is made up of a substance that we cannot see and do not yet understand.

How can astrophysicists make this bold claim? Until recently, any determination of the inventory of matter in a galaxy was based on counting the objects in the galaxy that either emit or absorb light. Lately, however, techniques have been developed that allow astronomers to measure directly the mass of a galaxy. By using stars as tracers of the strength of the gravitational pull of a galaxy, we can measure the galaxy's mass.

The total mass of a typical galaxy inferred in this fashion exceeds the mass of its stars and gas *by as much as a factor of ten*. The rest, the galactic "dark matter", is therefore by far the gravitationally dominant constituent of galaxies, including our own Milky Way. As outlined below, understanding this dark matter is the key to resolving many of the open questions in cosmology and astrophysics.

On a much larger scale, the average density of mass in the Universe determines whether the observed expansion will continue forever, or whether the Big Bang will be followed by a Big Crunch in which the Universe will collapse back onto itself. There are strong theoretical reasons to believe that the Universe is delicately balanced between these two possibilities, as this is the only condition that does not typically lead to either a runaway expansion or rapid recollapse on times much shorter than the observed age of the Universe. This theoretically favored condition of delicate balance between the expansion rate and mass density is termed a "flat Universe". Whether the Universe has elected to conform to our preferences is, however, a question that must be settled empirically, by observation and experiment!

It is important to bear in mind that there are two distinct dark matter problems. One, the galactic dark matter problem, arises in trying to understand the observed properties of galaxies. The other, the cosmological dark matter problem, comes primarily from comparing the total observed luminous mass with the amount needed to produce a flat Universe.

This is a Golden Age of observational cosmology. Some very basic questions have only recently passed from the realm of philosophy to scientific speculation to experimental inquiry. These questions include:

- What is the eventual fate of the Universe? Do we live in a flat Universe?
- How did the complex structure we see today on large scales (with galaxies distributed in vast tendrils and sheets) evolve from the uniform conditions that prevailed after the Big Bang?

- What are the constituents of the Universe? Is there a previously unknown family of elementary particles, generated in the cauldron of the hot Big Bang, that dominates the matter density of the cosmos, while so far eluding detection in accelerator experiments?

- What accounts for the shortfall between the total mass of a galaxy and the much smaller mass that resides in its stars and gas?

Dark matter, on both the galactic and cosmic scales, is a common thread that runs through all of the above questions. Dark matter governs the majestic rotation of the arms of spiral galaxies. It determines the interactions between neighbouring groups of galaxies in the cosmos. When the Universe was young, dark matter catalyzed the growth of galaxies and the evolution of large scale structure. Finally, the overall abundance of dark matter determines the eventual fate of the Universe.

Understanding the nature and distribution of dark matter are among the outstanding open questions in the physical sciences today. I am working with an international team of astronomers, physicists and computer scientists to address these issues. We have performed an ambitious experiment using gravitational microlensing, an important new tool that is described below.

We may have detected the dark matter of the Milky Way.

The present evidence is tantalizing but tenuous. Have we found the long-sought Galactic dark matter? Fortunately, recent advances in technology and techniques will enable us to answer this crucial question experimentally. This will require that we mount a next-generation gravitational microlensing dark matter search. This essay presents the case for doing so.

This is a special time in human history. For the first time we may be able to comprehend the grand cosmological scheme that is unfolding before us. Understanding the dark matter and the role it plays is critical to our taking this intellectual step forward.

The Dark Matter Puzzle, or "What's the Matter? "

The evidence for dark matter in galaxies started to accumulate in the mid-1970's. By the following decade it became clear that essentially all galaxies, including our own Milky Way, are surrounded by extensive halos of dark matter. Just as the orbits of the planets about the solar system can be used to ascertain the mass of the sun, astronomers can use the subtle orbital motions of stars to trace the gravitational strength of an entire galaxy. Measurements of the internal motions of many hundreds of galaxies provide incontrovertible evidence that stars, gas and dust alone cannot account for their observed properties. Dark matter halos are thought to be roughly spherical, extending far beyond a galaxy's stellar component. Just how far these dark matter halos extend, and therefore how much total mass they contain, is a topic of considerable current debate.

Attempts to measure the distribution of mass on much larger scales, to determine the overall matter density of the Universe, have proven more difficult. Recent results tend to favor the interpretation that the mass density falls short of the critical value needed for a flat Universe, but uncertainties are still large. How much does the material in galaxies (including their dark matter halos) contribute to the Universe's mass budget? To answer that question we will need better determinations of the amount of dark matter on both the galactic and cosmological scales.

An important aspect of the puzzle, that branches into the realm of elementary particle physics, is the nature of the dark matter. Is the dark matter made up of some exotic elementary particle that has eluded detection in accelerator experiments, or can we construct a viable picture using the known menagerie of particles? In order to answer this we need to know how much ordinary matter there is.

One of the triumphs of contemporary astrophysics has been the combination of theory and observation in determining the cosmic abundance of ordinary "baryonic" matter. Baryonic matter refers to material made of neutrons and protons, the building blocks of atoms. As the Universe cooled following the Big Bang, the abundances of light elements (namely isotopes of Hydrogen, Helium, and Lithium) were determined by the overall density of the baryons. Our theoretical understanding of nuclear physics has been brought to bear on studying the processes that governed the production of these light elements. Taking this in conjunction with recent observations of the actual cosmic abundances of these primordial elements, a consistent picture emerges in which the baryonic matter density is at most 5% to 10% of the critical value needed for a flat Universe.

If observations conclusively show that the overall mass density of the Universe significantly exceeds the amount thought to reside in baryons, then this will lend significant support to the idea that some new aspect of elementary particle physics must be responsible for most of the cosmological mass density. Interestingly, however, the baryonic fraction of the Universe is in rough agreement with the amount of mass thought to reside in dark halos of galaxies.

A key set of measurements in the coming decade will be invaluable in sorting out this puzzle. These include (1) experiments undertaken to identify the nature and amount of dark matter in our own galaxy, (2) measurements of the evolution of the geometry of the Universe, (3) studies of the large scale structure of the distribution of galaxies, and (4) detailed maps of the apparent temperature of the Cosmic Microwave Background, the afterglow of the Big Bang.

Each of these is an essential ingredient in understanding the *amount* of dark matter (on both the galactic and cosmic scales), and how it relates to the structure of galaxies and the fate of the Universe. In particular, measurements of the Cosmic Microwave Background promise to provide information on both the overall cosmological matter density and the baryonic fraction. These will be critical pieces of information in determining how much non-baryonic dark matter exists. While this determination of cosmological parameters will be a watershed in observational cosmology, it will not tell us the actual composition of the dark matter.

WIMPs versus MACHOs

There are two broad categories of dark matter candidates: astrophysical objects and elementary particles. One class of elementary particle dark matter candidates are WIMPs, for Weakly Interacting Massive Particles. This play on words has its origins in the fact that these particles are thought to have interactions with matter that are governed by the “electroweak” interaction, one of the fundamental forces of particle physics. Not to be outdone, the astrophysical community has dubbed their favored class of candidates MAssive Compact Halo Objects, or MACHOs.

Searching for dark matter is difficult. The only evidence we have for its existence comes from its gravitational influence on its surroundings. As far as we know it neither emits nor absorbs electromagnetic radiation, which precludes direct detection with the traditional tools of astronomy. If the dark matter is some exotic elementary particle then in order to have eluded detection it must interact with ordinary matter very weakly, if at all.

Despite these difficulties, a number of experiments are under way to search for particular dark matter candidates. Searches for elementary particle dark matter candidates exploit some trait associated with a given hypothetical particle. One class of experiments searches for evidence of rare interactions between WIMPs and a sensitive detector. As WIMP interaction rates are expected to be in the range of a few events per kilogram of target material per day, the main experimental challenge is in understanding and overcoming naturally occurring sources of radioactive background. These can either mask or masquerade as a detection of dark matter. WIMP experiments that have the requisite sensitivity and background discrimination are now moving from the prototype stage to full scale operation.

Looking through a Gravitational Lens to Search for the Dark Matter in the Milky Way

The Principle of Gravitational Microlensing

Perhaps the most dramatic progress in dark matter searches in the past 5 years has been in searches for astrophysical dark matter candidates, MACHOs, that exploit the one thing we know for certain about dark matter- that it exerts a gravitational force on its surroundings.

As stressed by Paczynski[1], if the dark matter halo of the Milky Way contains MACHOs, occasionally one will pass close to the line of sight between us and a distant star. The light coming from the background star will then be deflected due to the gravitational force from the intervening MACHO, as shown in Figure 1. This provides a very elegant and effective technique to search for MACHOs in the dark matter halo of the Galaxy, by looking for their gravitational effect on light from stars that reside beyond the halo.

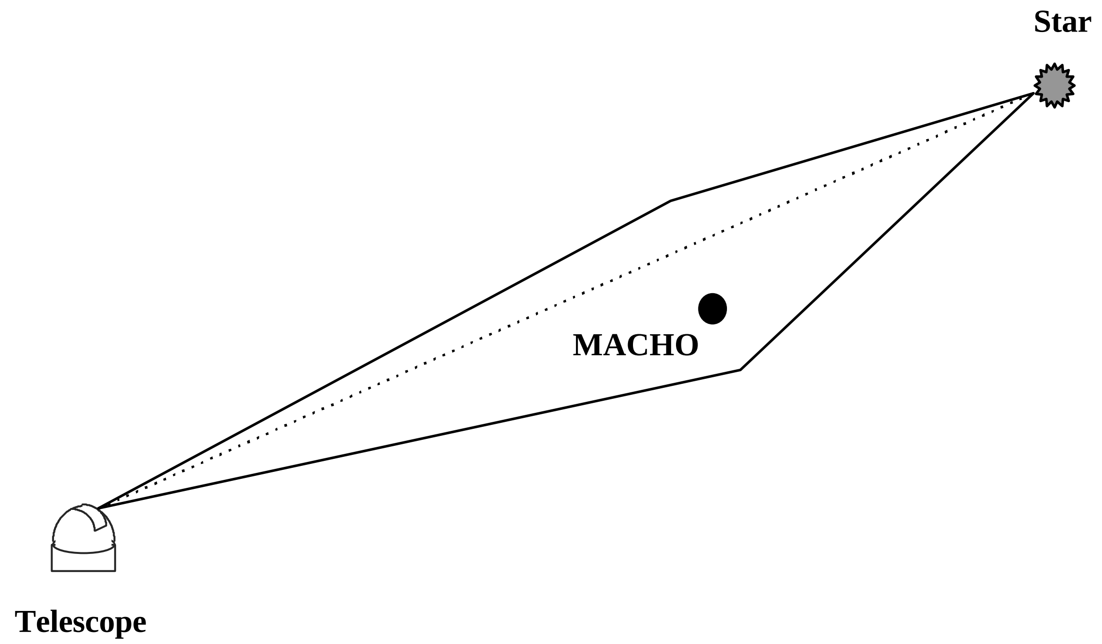

Figure 1. Schematic Representation of Gravitational Microlensing. Light traveling from a distant star is deflected in the presence of a MACHO, which acts as a gravitational lens. The star undergoes a transient brightening as a result of the lensing. This is the basis for searches for astrophysical dark matter candidates.

The deflection of the incoming light by the gravitational field of the MACHO is just as if an optical lens of astronomical proportions had been placed between us and the background star, making the star appear brighter. As this manifestation of gravitational lensing occurs in the immediate vicinity of our Galaxy, rather than over cosmological distances, this phenomenon is termed “gravitational microlensing”.

The observable signature of gravitational microlensing relies on the fact that this precise alignment between us, the intervening MACHO, and a background star is fleeting. The participants in this conspiracy are in relative motion. The line of sight sweeps along due to the motion of the Earth within the Galaxy, and any MACHOs in the dark matter halo would have speeds of hundreds of km per hour. This means that the signature of microlensing is a transient brightening of a background star, with a very specific shape predicted by General Relativity.

The duration of a microlensing event by a halo object with the mass of the planet Jupiter is expected to be about 3 days. The microlensing technique is therefore well suited to searching for astrophysical dark matter candidates, by making repeated nightly observations of stars using astronomical telescopes.

The effect of microlensing can be very substantial, with the apparent brightness of a star increasing by factors of 40 or more. The duration of a microlensing event depends on a number of factors, including the mass of the intervening lens, its position, and its speed across the sky. A slow, low mass lens can produce a signal that is indistinguishable from that of a more massive object that is moving rapidly, for example.

One great strength of this approach is that it is based on the one thing we do know about dark matter, namely that it exerts a gravitational influence on its surroundings. A microlensing search for dark matter is therefore sensitive to *any* population of astrophysical objects in the halo of the Galaxy, as long as their mass lies between that of the Earth and ten times the mass of the sun. This broad acceptance in the experiment, over 6 decades in mass, is unique among dark matter searches. It nicely brackets the expected mass range of the most heavily favored astrophysical dark matter candidates.

So much for the good news… while the signature of microlensing is unique, and the technique is sensitive to a broad range of masses, the expected *rate* of microlensing events is somewhat sobering. At any given time, even if the halo of our Galaxy were entirely accounted for by MACHOs, only about one star in a million would be significantly brighter due to microlensing.

Implementing a Search for Gravitational Microlensing

The experimental challenge in mounting a search for dark matter using gravitational microlensing is to monitor the brightness of many tens of millions stars on a nightly basis, and then to search through the data to find the needle in the haystack: the handful of stars that brighten due to the lensing effect of an intervening MACHO. Just to make the experiment even more interesting, there are intrinsic sources of stellar variability that must be successfully discriminated against. Fortunately, there is no variable star that looks like a microlensing signal.

The ingredients for a successful search for microlensing include: (1) A telescope dedicated to the endeavor, to allow nightly measurements, (2) A wide field high sensitivity camera system, for efficient measurements of many stars at a time, (3) Computer resources at the scale necessary to process and store the torrential data stream, and (4) A population of millions of stars that lie beyond most of the Milky Way's dark matter halo, while close enough for individual stars to be resolved and measured.

A search for MACHOs using gravitational microlensing was feasible by the late 1980's, due to progress in computer and detector technology. Silicon detectors, namely Charge Coupled Devices (CCDs), provided astronomers with a powerful alternative to film. These detectors have roughly 100 times the sensitivity of film, and provide immediate digital data that are amenable to computer analysis.

At the same time, high end computing power was becoming ever more affordable. The computing aspect of a microlensing search is daunting. There is a premium on detecting ongoing microlensing events as they are occurring. This requires first extracting the ten million stellar images from 5 Gbytes of raw image data per night. The most recent measurement on *each* star must then be compared with the recorded history of prior observations. Any stars that exhibit a brightening are then be subjected to further analysis and filtering.

The Macho Project

Recognizing that technology was at hand for a microlensing search, a team of astronomers, physicists and computer scientists from the US and Australia banded together to undertake the Macho Project. The objective of the endeavor was to test the hypothesis that the dark matter halo of our Galaxy comprises astrophysical objects. As one of the original members of the Macho team I supervised the construction of what was at the time by far the largest CCD camera in the world, one that produced 77 Megabytes of data per frame. This camera is mounted on the 50-inch telescope at the Mt. Stromlo Observatory in Australia, to monitor stars in the Large Magellanic Cloud, the Small Magellanic Cloud, and the center of the Milky Way. The Macho Project started taking data in 1992, and is scheduled to cease operation at the end of 1999.

The Large and Small Magellanic Clouds are nearby galaxies, visible only from the Southern hemisphere, which contain the millions of extra-Galactic stars that are needed as a backdrop for a successful microlensing search. The lines of sight towards the Magellanic Clouds form significant angles with the disk of the Milky Way, so microlensing along those lines of sight is dominated by halo objects. On the other hand, by looking towards the center of the Milky Way as well, the experiment is sensitive to microlensing by ordinary stars in the disk of the Galaxy. The Macho Project monitors stars along these three lines of sight, and has now detected instances of microlensing in each of these directions.

Microlensing Has Been Detected

At the time of this writing our Macho team has amassed over 5 Terabytes of raw data, and we have detected more than 200 candidate microlensing events, over ten times more than any competing project’s tally. The overwhelming majority of events are seen towards the Galactic center, the result of microlensing by ordinary stars in the disk of the Galaxy. An example of the brightening of a star in the Galactic center due to a microlensing event is shown in Figure 2. This event was detected well before peak using the real-time data analysis capability we have developed. This allowed multiple telescopes worldwide to concentrate on the event, obtaining detailed information about the gravitational lensing system.

This microlensing event, and hundreds like it, have shown that the experiment works. We know how to extract microlensing events as they are happening, and we communicate information about ongoing events to astrophysicists worldwide.

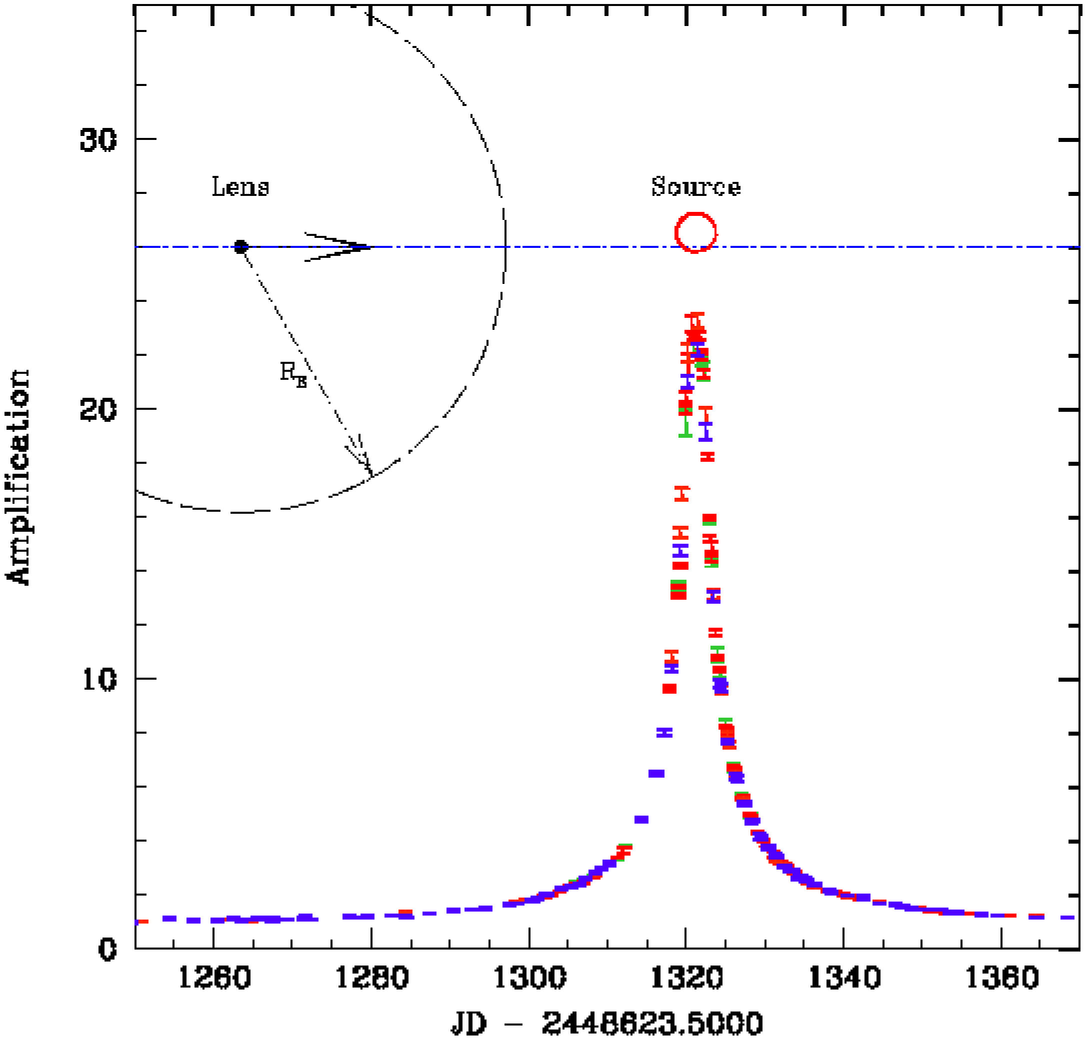

Figure 2: An Example of a Microlensing Event.

This Figure shows the light curve of an actual microlensing event, detected in a star in the Galactic center. The figure shows the relative observed brightening of the star over many days. The data points are drawn from a variety of telescopes around the world. The high density of sampling allows for a detailed comparison with the predicted shape of the brightening, from General Relativity. The agreement is excellent. (From Reference 2.)

The field of microlensing is growing rapidly. Even though the first candidate events were reported in only 1993, we have already progressed to the stage where certain exotic microlensing events lie at the intellectual frontier. For example, during a microlensing event that lasts many tens to hundreds of days, the Earth's orbit around the sun produces a slight skew in the observed light curve. This subtle perturbation can be used to determine whether the lens is nearby or far away, for a given mass of the lensing object. As described below, this effect will be critical to understanding the puzzle that is presented by the current microlensing results.

Besides the main objective of the survey, i.e. searching for gravitational microlensing, the project has also produced an unprecedented catalog of well-sampled variable stars. This by-product dwarfs all previous surveys of stellar variability. In addition, microlensing may well provide a new window into the detection of extra-solar planetary system. These topics will be treated briefly, before turning to the dark matter results from the Macho Projcet.

Variable Stars from Microlensing Survey Data

The Macho Project has made more sequential measurements of stellar brightness than the entire previous history of astronomy. It is therefore not surprising that the data set constitutes an unprecedented resource for the study of stellar variability. While this was not the primary goal of the project, from the outset we knew this would be an important contribution to astronomy. Examples of important variable star studies that have been made possible by the quality and sampling of the Macho data include work on periodic variable stars, eclipsing binary stars, X ray sources, and the detection of multiple novae and supernovae. We have detected many tens of thousands of variable stars, nearly all of them previously unknown.

A variety of research programs have been carried out using the Macho Project's variable star data set. One example is a study of the detailed behavior of a class of periodic variable stars called Cepheids. These stars exhibit a tight correlation between their pulsational period and their intrinsic brightness. Measurements of the period and the apparent brightness of Cepheids can be used to extract a distance to the galaxy containing the periodic variable stars. The unprecedented temporal sampling and completeness of the Macho data set have allowed new insight into the fundamental mechanism of pulsation in these stars. This has a direct bearing on our understanding of the cosmic distance scale.

Using Microlensing to Search for Planets Around Other Stars

Among the significant recent observational developments in astronomy was the announcement of the likely detection of planetary companions to a number of nearby stars. The existence of other planetary systems has long been hypothesized, of course, but only recently have we had experimental confirmation of them. The main technique that is currently used to search for extrasolar planetary systems (measuring radial velocities) is only effective for bright stars, and is limited to giant Jupiter-sized planets. An Earth-like system would be undetectable using this approach.

Imagine that one of the many cases of gravitational microlensing by ordinary stars, detected towards the Galactic center, was due to a star that had a planetary companion. This could perturb the shape of the detected microlensing light curve, as the light would be deflected by both the main star and its companion planet. Detailed calculations show that a significant fraction of such cases would be detectable, but that the perturbation of the light curve would only last a few hours. Furthermore the technique is sensitive to Earth-mass planets, and is unique in this regard.

Using microlensing to search for extra-solar planetary systems is in its infancy, but is an exciting and promising technique. We have identified instances in light curves of microlensing towards the Galactic center that might be due to lensing by planets around distant stars, but the analysis of these events is still in progress.

Microlensing Towards the Galactic Center- A New Probe of Galactic Structure

By mapping out the event rates towards the Galactic center, along different lines of sight through the disk of the Milky Way, microlensing can be used as a powerful new probe of Galactic structure. Initial microlensing rates reported by both the Macho collaboration [3] and a competing team (the OGLE survey) both exceeded earlier predictions. These early theoretical predictions had made the unwarranted assumption that the Milky Way is symmetrical, shaped like a dish. Once the microlensing results were announced, astronomers soon realized that a more realistic model was needed, specifically one that includes an elliptical body of stars in the center of the Galaxy. After including the contribution of this “Galactic bar” the models were brought into agreement with the microlensing data.

The constraints on Galactic structure that are provided by microlensing have an indirect impact on our understanding of the Milky Way’s dark matter. By probing directly the *mass* distribution in the disk of the Galaxy, we can better understand the interplay between dark matter and stars in supporting the observed overall rotation of the Galaxy. This in turn can be used to constrain models of the dark matter halo.

Microlensing Towards the Magellanic Clouds - Testing the MACHO Hypothesis

While the lines of sight through the disk towards the Galactic center have produced the overwhelming majority of the microlensing events observed to date, a handful of events seen towards the Magellanic Clouds may be the key to understanding the nature of the Milky Way’s dark matter halo. Since microlensing towards the Magellanic Clouds would be dominated by MACHOs in the halo, this is the most sensitive way to detect and/or constrain their existence.

Over the course of two years of observations of stars in the Large Magellanic Cloud (LMC), our Macho team has produced[4] the most stringent results to date on the possibility that astrophysical objects, rather than elementary particles, might make up the dark matter halo of our Galaxy. We have carried out over one thousand observations of more than 9 million stars in the LMC. This data set has led to two major dark matter results, described below.

No Low Mass MACHOs

It is often the case in science that tremendous progress is made by *eliminating* possibilities. The search for dark matter is no exception. In our LMC data set we have searched for microlensing events with a duration ranging from hours to two hundred days. We see no LMC events that last less than 20 days.

Using the connection between lens mass and event duration we can exclude astrophysical objects with masses between one millionth to one tenth of the mass of the sun as making up the dark halo of the Galaxy. The most favored astrophysical dark matter candidates, brown dwarfs and Jupiter-sized objects, fall squarely within this excluded range. These were thought to be prime dark matter candidates as they are not massive enough for their internal (gravitationally produced) pressure to ignite the nuclear burning that makes stars shine. This was thought to be a natural explanation for their having evaded direct detection. Evidently, based on the microlensing results, this speculation was not correct. Excluding such a broad range in dark matter candidates, with high statistical confidence, is a major step forward in dark matter science. If this were the only scientific result from the Macho project it would be rightfully regarded as a very successful endeavor.

An Excess of Long Duration Events - The Detection of the Galactic Dark Matter?

We did, however, detect 8 microlensing events towards the LMC, when only about 1 event was expected from lensing by known stellar populations. These events typically last 80 days, corresponding to MACHOs with a few tenths of a solar mass, although the uncertainty in the mass is quite large.

Is this the long sought Galactic dark matter? Based on models of the structure of the Galaxy and its dark halo that were popular before the microlensing results were announced, the answer would seem to be yes. Taken at face value the event rate corresponds to our having detected at least half of the Galaxy’s dark matter halo! Should this prove to be the case, one of the major contemporary astrophysical and cosmological puzzles will have been solved.

If we have seen MACHOs in the halo of the Galaxy, what could they be? Much of the power of the microlensing technique is its insensitivity to the detailed nature and structure of the lensing object, however at this stage that becomes a disadvantage. Speculation about the composition of the MACHOs is therefore based on other knowledge of the different species in the astrophysical zoo, but it is entertaining and even instructive to contemplate the various possibilities.

One alternative is that the MACHOs are the endpoint of stellar evolution from some very early population of stars, perhaps white dwarf stars that have exhausted their nuclear fuel, or even neutron stars. A problem with this scenario is that during their evolution such stars would have suffered significant mass loss, blowing off major amounts of material that contain heavy elements. There are stringent limits on the amount of interstellar matter, and scenarios that invoke an early population of stars have difficulty in confronting these observational constraints.

Another possibility is that MACHOs are some gravitationally bound state of matter that never passed through a stellar phase. This somewhat exotic class of objects includes “primordial black holes” that were formed early in the history of the Universe, and have been darkly coasting along ever since. Such objects would have been virtually impossible to detect by looking for any emitted light, but they would act as perfectly decent gravitational lenses. In this case the MACHOs might be exempt from constraints imposed on the Baryonic content of the Universe, as they could in principle have been formed in an era where those bounds simply would not apply.

There are, however, other possible interpretations of the observed microlensing event rate that do not invoke the dark matter halo. Particularly when we are dealing with only a few detected events the statistical uncertainties are still fairly large. Possibilities for accounting for the excess lensing events with ordinary stars rather than halo MACHOs include

- lensing by foreground LMC stars,
- lensing by some foreground dwarf galaxy or stellar debris from the LMC, or
- lensing by some previously unappreciated extended stellar population of our own Galaxy.

These are testable hypotheses and it is imperative that we distinguish between these alternatives and the dark matter interpretation of the observations.

The Path Forward: A Next Generation Microlensing Survey

Why Do Another Experiment?

The compelling motivation for a next generation microlensing survey is to determine whether the excess of events seen towards the Magellanic Clouds is due to the dark matter halo of the Milky Way. Why do we need a new experiment to answer this question?

Based on our current event rate, by the end of the 1999 the Macho Project will likely have detected about two dozen microlensing events towards the LMC. Perhaps 3 or 4 will be seen towards the SMC. While this significantly exceeds the rate expected from known stellar populations, it is simply too few to definitively test the idea that the lensing is due to MACHOs in the halo of our Galaxy.

There are three reasons to increase the number of events towards the LMC and SMC:

- We can address the hypothesis of lensing by foreground LMC stars by mapping out the event rate across the face of the LMC. A detailed study of how the event rate depends on the density of LMC stars will allow a definitive test this possibility. This will require many tens of LMC events to achieve the requisite statistical significance.

- A comparison of the event rates between the LMC and SMC lines of sight probes the flattening of the lensing population. A disk-like distribution of MACHOs would have a very different ratio of rates than would a halo population. To make a definitive comparison will require hundreds of events.

- Finally, about 10% of the events we have detected to date show structure that cannot be accounted for by the simple point-mass, point-source picture given in Figure 1. These exotic lensing events are now well understood, and are very useful. In these cases the degeneracy between lens position, mass and velocity breaks down, and we can learn a great deal about the lensing system. In particular, for long events the orbital motion of the Earth introduces a measurable perturbation that is very different for nearby lenses versus distant lenses. This is a very powerful way to establish whether the lensing population is in the immediate foreground (perhaps a wisp of stars from the Galaxy), or is far away (as expected for halo MACHOs). Taking full advantage of this phenomenon will also require the detection of roughly one hundred events.

We need between 100 and 200 Magellanic Cloud events in order to achieve these important goals. The present experiment would need to run for decades to detect the requisite number. Other ongoing microlensing searches have apparatus that is essentially similar to that of the present Macho Project. Once they come into full operation they will have roughly comparable event rates. A new experiment is necessary, building upon the successes of the existing program, to achieve these objectives.

There are two possible answers to the experimental question of whether the excess event rate we have seen is due to dark matter MACHOs. It is worth stressing that with *either* outcome this will be a crucial and successful experiment. If the results support the halo MACHO hypothesis, then one piece of the dark matter puzzle will be firmly in place. On the other hand, if further intense scrutiny shows that the detected signal is due to some previously unappreciated ordinary stellar population, then microlensing searches will have essentially eliminated astrophysical objects as viable dark matter candidates. This would also be a great step forward in unraveling the mystery of dark matter. We will win in either case.

The Plan

Fortunately a revolution in technology is not necessary to mount a search that would detect events at well over ten times the current rate. We will need to monitor over ten times as many stars per night than are scanned by the existing Macho program. A number of performance enhancements relative to the Macho Project will make this possible, including

- Doubling the camera's sensitivity by using cutting-edge CCD technology
- Doubling the camera's field of view, to one full square degree
- Halving the time spent reading out the CCD camera, thereby increasing efficiency
- More than tripling the experiment's light gathering power, with a 2.4 meter telescope
- More than tripling the number of distinct stars per frame by operating at a site with minimal atmospheric degradation of image quality
- Reducing the background in the images by operating at a darker site, and
- Establishing very close coordination between the survey and the network of followup telescopes.

The next generation microlensing survey should easily surpass the total number of Magellanic Cloud events detected in the past 5 years during its first year of full operation.

The challenges in carrying out this program include the fabrication of the new instrument, and obtaining access to the requisite (large!) amount of telescope time at an outstanding astronomical site. In addition, the raw data rate and database management problems will be an order of magnitude more difficult to handle than in the current microlensing survey. While demanding, these are all manageable problems given the right combination of personnel, resources, and contemporary technology. This convergence is now taking place, and a capable team of scientists is laying the necessary groundwork for the next-generation experiment.

The Site and The Telescope

Turbulence in the atmosphere degrades astronomical images. The superb resolution obtained by the Hubble Space Telescope is possible only because it orbits above the swirling layers of air that plague ground-based observatories. Unfortunately the field of view of the Hubble is far too small to carry out a search for microlensing. The penalty extracted by the atmosphere depends very much on the location of the observing site. Ideal sites for optical observatories are in high, dry places where the topography rises rapidly above the ocean or a plain.

A long-standing difficulty in designing, building and operating telescopes for optical astronomy has been to actually realize the image quality potential of a site. There has been much recent progress in understanding the aspects of telescope design that influence image quality. A new generation of telescopes are being engineered with the express goal of delivering images that are limited only by the characteristics of the site, not the telescope.

The performance of the next generation microlensing survey will depend critically upon the image quality delivered to the camera system. The best astronomical sites in the Southern hemisphere are in Chile. The Cerro Tololo Interamerican Observatory (CTIO) is the US federally funded facility in Chile that supports astronomy in the Southern sky. Tests of the stability of the upper atmosphere in Chile indicate that exquisite image quality should be achievable there.

The next-generation microlensing team is working in tandem with the National Optical Astronomical Observatories (of which CTIO is a part) to construct a new technology telescope with an aperture of 2.5 meters, in Chile. During the times when the Magellanic Clouds are visible, the telescope will be devoted to the microlensing survey until the target number of events are detected. Present plans place this telescope on the same ridge that was selected for the southern Gemini telescope, the flagship 8 meter diameter US telescope that is now under construction.

The Camera System

The construction of the instrument described above is a serious technical challenge. The CCD detectors used in contemporary astronomical instruments are the largest integrated circuits made, and are remarkable devices. They convert incident light into electrical charge, in proportion to the light intensity. They perform this conversion of light into an electrical signal with an efficiency of over 90%. The resulting charge can be determined at the level of a few electrons. Individual detectors with 2048 X 4096 pixel formats are becoming common.

In the camera being proposed for the next generation microlensing survey, eighteen such detectors must be carefully aligned within a vacuum system. They are then cooled to about –100 degrees C in order to suppress background signals that are thermal in origin. This focal plane mosaic array of detectors must be interrogated by a readout system that converts the light-generated electrical charge into digital data that are suitable for computerized data analysis. These data will typically flow to the analysis computers at the rate of 20 Gigabytes per night.

A number of innovative features will be incorporated into the instrument. For example, any image degradation from slight vibrations and motions of the telescope will be suppressed by making compensating shifts in the charge on the CCD detectors, while the image is being exposed. Also, a different subsystem will continually ensure that the image is kept in focus. This is consistent with the survey-wide emphasis on image quality.

While this camera will be larger, more sensitive, and more efficient than any existing astronomical instrument, it is a natural next step in the evolution of astronomical instrumentation for wide field imaging. The camera system is one of the critical technological advances that will enable the next generation microlensing survey to go forward.

Computing

There are two main challenges on the data analysis and data management front. The first is to install sufficient brute-force computing power to carry out real-time analysis of the raw image data. The second is to devise a data storage system that efficiently allows scientists access to the accumulated sequence of stellar observations.

The on-line data storage task will likely require over a Terabyte of magnetic disk. This is more than one thousand times more than the 1 Gbyte drives that are shipped with typical personal computers. Interestingly, making backup copies of data sets of this size is one of the major challenges in carrying out the project.

A networked array of twenty high end PC-type computers is adequate for the experiment. By allocating one CPU to each of the eighteen detectors in the camera, the system is very well suited to taking a parallel approach to the computational task.

Timetable

If all goes well, current plans call for the installation of the telescope at CTIO in 2001. Camera fabrication would occur during calendar 2000 and 2001. After six months of shakedown and integration the next-generation microlensing survey would commence in earnest in late 2001 or early 2002.

Summary and Conclusions

The dark matter problem is one of the pivotal open questions in the physical sciences today. We know that most of our Galaxy is made of dark matter. We know that the average cosmic density of dark matter determines the eventual fate of the Universe. We do not know what dark matter is, or how it is distributed. This has spurred a number of efforts to try to detect either elementary particle or astrophysical dark matter candidates.

A new tool in this quest, gravitational microlensing, has produced two important results to date that bear on astrophysical dark matter candidates. First, the lack of any short duration microlensing events has eliminated brown dwarfs and similar objects from contributing in any significant way to the dark halo of the Milky Way.

We do, however, see more long duration events than one would expect from the conventional picture of how stars are distributed in the Galaxy. This could be our first hint of an actual detection of the dark halo of the Galaxy. Microlensing is the only dark matter search technique that has produced a robust and persistent signal. With only a handful of events, however, it is difficult to distinguish between this interpretation and more conventional explanations. Doing so will require a tenfold increase in the detection rate.

A next-generation microlensing survey, conducted with state-of-the-art instrumentation at an outstanding astronomical site, would provide the number of events needed to test whether we have detected the dark matter. The case for performing this experiment is compelling, as it could provide us with the key to understanding some of the most profound questions mankind has considered.

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