The MACHO Camera System: Searching for Dark Matter

The award-winning MACHO camera system—an integrated, two-color, digital imaging system with 32 million pixels—is the leader in the experimental search for cosmic dark matter. During its first three months of operation, this camera system recorded more photometric measurements than were previously made in the history of astronomy.

ONE of the most pressing astronomy and cosmology issues in the 1990s is to identify and account for the "missing" cosmic matter. This unsolved problem arises from overwhelming evidence suggesting that some kind of ubiquitous and invisible matter surrounds and permeates the bright, observable disks of our own and other spiral galaxies. To put this extraordinary problem of cosmic bookkeeping into its most basic terms, we simply have no information about what makes up most of the universe.

The most compelling evidence for the missing matter comes from two different methods for studying our galaxy, the Milky Way. Using one method, astronomers can determine the mass of an object (for example, the Sun) by analyzing the planetary orbits around it. Similarly, they estimate the mass of the Milky Way by studying the nearly circular motion of the visible stars and gas around the galaxy's center and by directly applying Newton's laws. The value astronomers obtain in this manner is the total mass of the Milky Way.

A second way to estimate galactic mass is to measure the total amount of starlight emitted by the galaxy. Astronomers know approximately the ratio of starlight to stellar mass; thus, they can estimate the mass of stars that emit light. The total from this second method, called the luminous mass, is only about 10% of the total mass determined by motion and Newton's laws. In other words, more than 90% of the mass of the Milky Way, which must exist because of its gravitational pull, cannot be seen by the techniques that have been available. The unseen substance is referred to as "dark matter." The conclusion that there is dark matter in the Milky Way is among the most secure in modern astronomy and astrophysics.

If the dark matter were made of normal stars, dust, or gas clouds, it would be luminous and readily detected. Not only is the substance nonluminous, but astronomers also believe that most of the invisible components do not even lie in the plane of the Milky Way, where most stars are found. The following argument leads astronomers to that conclusion. Theoretical studies show that flat systems are dynamically unstable. The age of our galaxy tells us that the Milky Way is now stable, and stable systems are nearly spherical. Therefore, most of the matter in our galaxy is spread out through an encompassing sphere, known as the galactic halo. But what, exactly, makes up the dark halo?

In the past, astronomers have come up with several ideas to explain the nature of dark matter and the fact that it does not emit or absorb detectable amounts of electromagnetic radiation. A fashionable and widely held notion is that it could consist of hypothetical elementary particles not yet detected. This idea is called the exotic matter theory. Axions, massive neutrinos, and weakly interacting massive particles (known as WIMPs) have been suggested as candidates. The mass of an axion, if it really exists, is proposed to lie between about 10^{-12} to 10^{-9} the mass of an electron. WIMPs would weigh more than 10,000 times the mass of an electron.

An alternative and much less exotic idea in many respects is that the dark matter could be made of material in the form of bodies with masses ranging from that of a large planet to a few solar masses. One candidate is massive objects like brown dwarf stars (also called degenerate dwarfs), ranging from 10 to 80 times the mass of Jupiter; these objects are too small to heat up to nuclear-burning temperatures, which would make them luminous. The compact remnants of burned-out massive stars, such as neutron stars or black holes, have also been suggested.

Indeed, the dark matter could even consist of macroscopic objects similar to the planet Jupiter itself. Whereas Jupiter is visible to us because it is relatively close to Earth, the distant Jupiter-like objects making up the dark matter would remain invisible at the astronomical distances under consideration (about 30,000 light years). The term MACHO, which stands for massive compact halo objects, has been adopted as a generic term for all the proposed dark, massive objects in the Milky Way's galactic halo whether they are like Jupiter or not. Because temperatures at their centers are not hot enough to ignite nuclear fusion, MACHOs remain dark and difficult to detect.

Even though MACHOs cannot be directly observed through a telescope or otherwise, it is nevertheless possible to infer their presence indirectly. This article describes a breakthrough scientific system we built that couples the power of large-format digital imagers with low-cost, high-speed minicomputers. This new system will definitively answer the question of whether MACHOs make up some or possibly all of the dark matter, or, as one astronomer puts it, reveal the hiding place of the "halo grail."

Gravitational Microlensing

In 1986, an astrophysicist at Princeton University, Bohdan Paczynski, suggested a way that it might be possible to identify MACHOs.[1] Through the gravitational microlensing effect, Paczynski noted, objects with masses ranging from one millionth to one hundred times that of the Sun might be detected even if the objects themselves are nonluminous.

In essence, the gravitational field of a MACHO acts as an amplifying (converging) lens. Gravitational microlensing occurs when a MACHO moves close to the line of sight from an observer on Earth to a background star outside our galaxy, as shown in Figure 1. The paths of light rays from the star (essentially a point light source) are bent by the MACHO (essentially a point mass), and the star appears to brighten as the dark object moves across the field. The term "microlensing" is used because the lensing angle is too small to be observed; in other words, the bending angle is so small that no image distortion is seen. Even though we cannot see a change in the shape of a star subject to microlensing, we should be able to see the star getting brighter.

The amplification of light by a gravitational lens can be significant, but microlensing events are extremely rare. At any given time, only about one star in two million is microlensed. Those that are amplified can have their brightness increased by a factor up to several times the unamplified flux.

The amplification of apparent brightness of a background star is also transient—a most important feature. As the MACHO moves out of the line of sight from an observer to the distant star, the star returns to its original intensity. Because all objects in our galaxy are in motion, a highly characteristic pulse occurs in the brightness of the star, providing the MACHO signature. The duration of a microlensing event depends, in part, on the mass of the lens. However, duration is also affected by other parameters, such as the MACHO velocity transverse to the line of sight and the distance from Earth to the dark object. A rough estimate of the transverse velocity would be in the range of 200 km/s. For typical models of the galactic halo, the time of a microlensing event t is given as:

$$t\ (\text{days}) \approx 100 \sqrt{M_{\text{macho}}/M_{\text{sun}}} \quad ,$$

where M_{macho} is the mass of the MACHO and M_{sun} is the mass of the Sun. For example, if the dark object's mass equaled that of Jupiter, the event would be about two days.

Measuring event duration gives us a mass estimate that we could not obtain by any other technique. Before any experiments began, gravitational microlensing durations were predicted to range from a few days (for objects as massive as Jupiter) to weeks (for more massive objects).

Optimal background sources to study MACHO microlensing events are the stars of the Large and Small Magellanic Clouds—small galaxies at the outer edge of the halo. The photograph in Figure 2 shows what the Large Magellanic Cloud looks like from the point of view of an observer on Earth. A perspective of the relative location of Earth in the Milky Way, the galactic halo around and beyond the Milky Way, and the Large Magellanic Cloud can be gained from this figure. This galaxy is distant enough to exploit the gravitational microlensing effect, and the line of sight is favorable because it traverses much of the halo. In addition, the Large Magellanic Cloud is close enough that millions of individual stars can be seen using ground-based telescopes.

The MACHO Signature vs Astronomical Background

Some classes of stars spontaneously vary in brightness. An important challenge in the search for MACHOs is to differentiate the microlensing events of interest from any astronomical background variations. Fortunately, we can distinguish microlensing light curves from the background of variable stars because microlensing events that constitute the MACHO signature are achromatic (i.e., do not change color over time), symmetric in time, and nonrepeating. This kind of brightening is unlike any known variable star phenomena. In addition, a microlensing light curve is described by only three parameters:

- Maximum amplification.
- Time of maximum amplification.
- Event duration.

Much like understanding MACHOs themselves, exploring the astronomical background also opens a scientific gold mine. By doing so, we can uncover important data on the variability of all celestial objects, including regular and variable stars, explosive outbursts in stars, and quasars.

Scope of the Problem

The search for MACHO events is daunting. To understand the extent of the problem and the many scientific components required to investigate MACHOs, refer once again to Figure 2, which is an artist's attempt to place the extraterrestrial elements of our MACHO system in their galactic context. Back on Earth, the scope of the scientific problem entails:

- Obtaining an extraordinary number of images each night through dedicated use of a telescope in the Southern Hemisphere. (The Magellanic Clouds are visible only from the southern sky).
- Creating an optical imaging system with an exceptionally wide field of

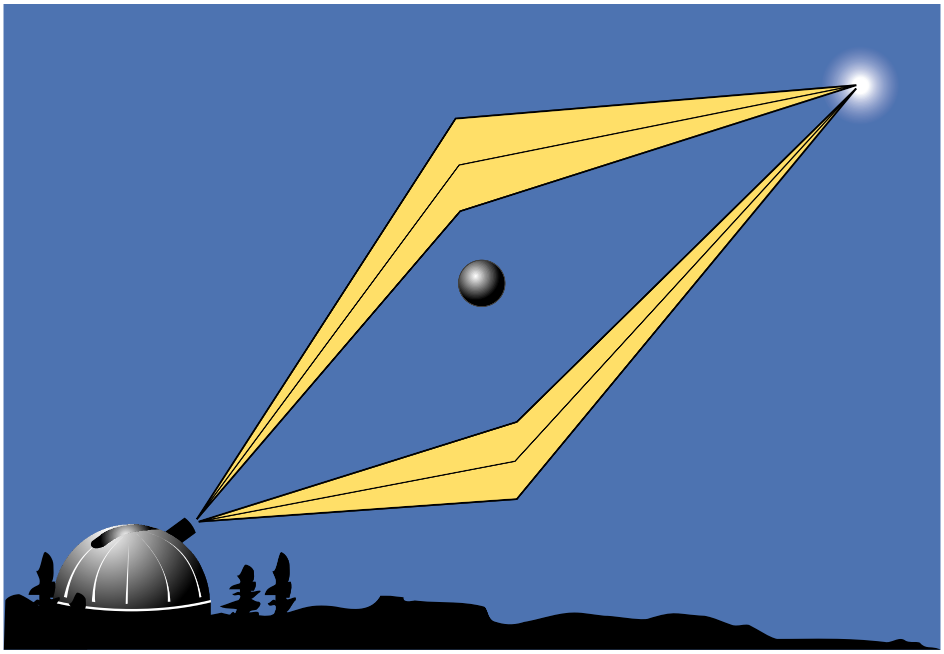


Figure 1. The paths of light rays from a star outside our galaxy are bent by a MACHO located close to the line of sight between the star and an observer on Earth. In this diagram, the amount of bending is greatly exaggerated to illustrate the concept. The actual angle between the two light rays from the star is a tiny fraction of a degree—so small that the star continues to look like a point but becomes temporarily brighter until the MACHO moves out of the line of sight. Because the gravitational field of the MACHO temporarily acts as an amplifying lens, the phenomenon is called gravitational lensing. The highly characteristic pulse in the brightness of the star provides the MACHO signature.

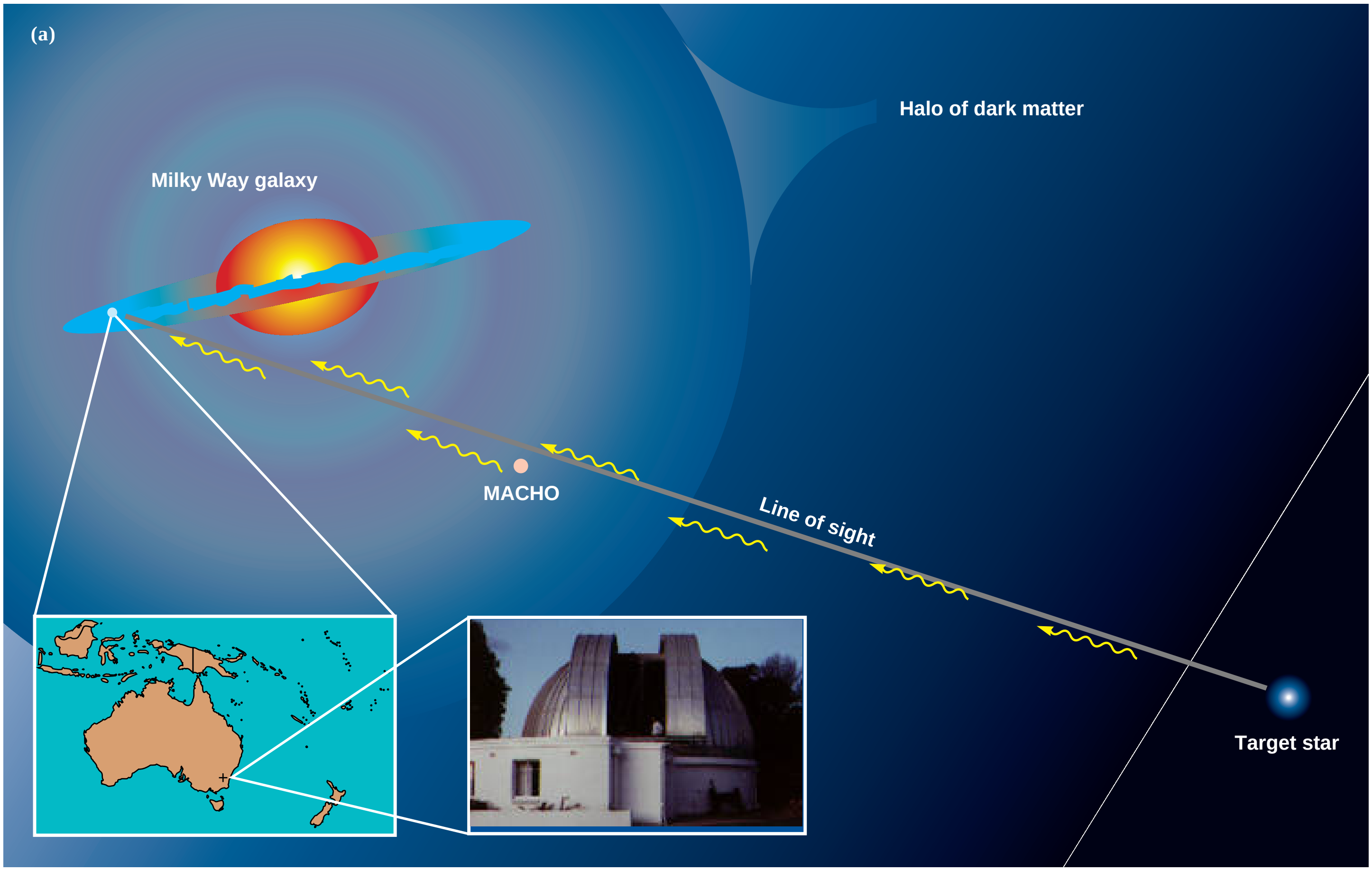


Figure 2. (a) Relative positions of our planet in the Milky Way (left), a potential gravitational lens (a MACHO) in the galactic halo (near center), and a target star in the Large Magellanic Cloud (right). The undetected matter of our galaxy, the dark matter we are investigating, is distributed in a spherical halo surrounding the observable disk of stars. This halo extends around and beyond the Milky Way to some unknown distance. The target star is located in the Large Magellanic Cloud about 45,000 parsec (pc) from the solar system (1 pc = 3.258 light years or 3.086 ¥ 10^{13} kilometers, so the target star is about 150,000 light years away.) Photograph (b) shows what the Large Magellanic Cloud looks like from the perspective of an observer on Earth. This extragalactic cloud is a small galaxy at the outer edge of the Milky Way's halo. It is distant enough to exploit the gravitational microlensing effect yet close enough to Earth that individual stars can be seen using ground-based telescopes.

(b)

view and a large detector to yield an imaged area about 100 times larger than that at most telescopes.

- Designing and fabricating very high-quality, large-format digital imaging cameras by fully exploiting the newest technologies.
- Obtaining, storing, and analyzing massive amounts of data with new algorithms.

The search for MACHOs requires making an unprecedented number of regular photometric measurements on stars for several years. But what, exactly, constitutes enough measurements? Our principal technical challenge arose when we demonstrated that “enough” in the context of our search meant exceeding the total number of photometric measurements made in the history of astronomy by two orders of magnitude. Because we did not know exactly what event durations were most probable, we proposed to use a variety of sampling techniques, ranging from several times an hour to once every several nights. Existing equipment and instruments could not do this work.

Finding a Solution

In 1990, we began collaborating with groups at the Center for Particle Astrophysics from the University of California campuses at Santa Barbara, Berkeley, and San Diego. An essential part of this collaboration involves researchers at the Mount Stromlo and Siding Spring Observatories from the Australian National University in Canberra. We started by designing an innovative optical system for the 1.27-m reflecting telescope at this university. The following year, we designed and fabricated two charge-coupled device (CCD) cameras, assembled a system to acquire and process data, and developed data-analysis software.

The result of our efforts is the MACHO camera system, a fully integrated, two-color digital camera and image-processing system. This R&D 100 award winner for 1993 (see the box on p. 13) is the only optical imaging system that fully exploits the new generation of large-format CCD imagers. Our search for MACHOs in the dark matter, which involves gathering terabytes of data and nearly 10 billion photometric measurements, commenced in the autumn of 1992. On completion, distilled results from the experiment will definitively answer the question of whether MACHOs make up the enigmatic dark matter of the Milky Way.

Telescope and Optics

The Magellanic Clouds are only visible from the southern sky. To make the number of photometric measurements our survey requires, we needed extended use of a telescope in the southern hemisphere and an exceptionally wide field of view. We arranged for four years of dedicated use of the telescope (Figure 3) at the Mount Stromlo and Siding Spring Observatories.

The mirror of the Great Melbourne Telescope is a classic parabolic reflector. A parabolic mirror does not have good off-axis performance, so we needed to design a system of

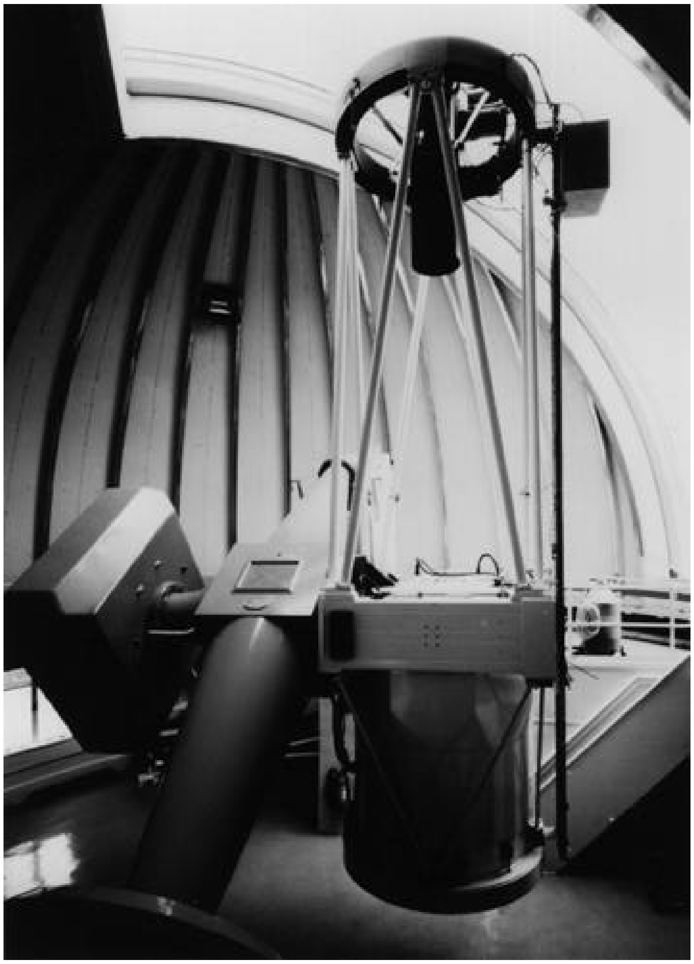


Figure 3. The newly recommissioned 1.27-m telescope at Mount Stromlo, Australia, formerly called the Great Melbourne Telescope.

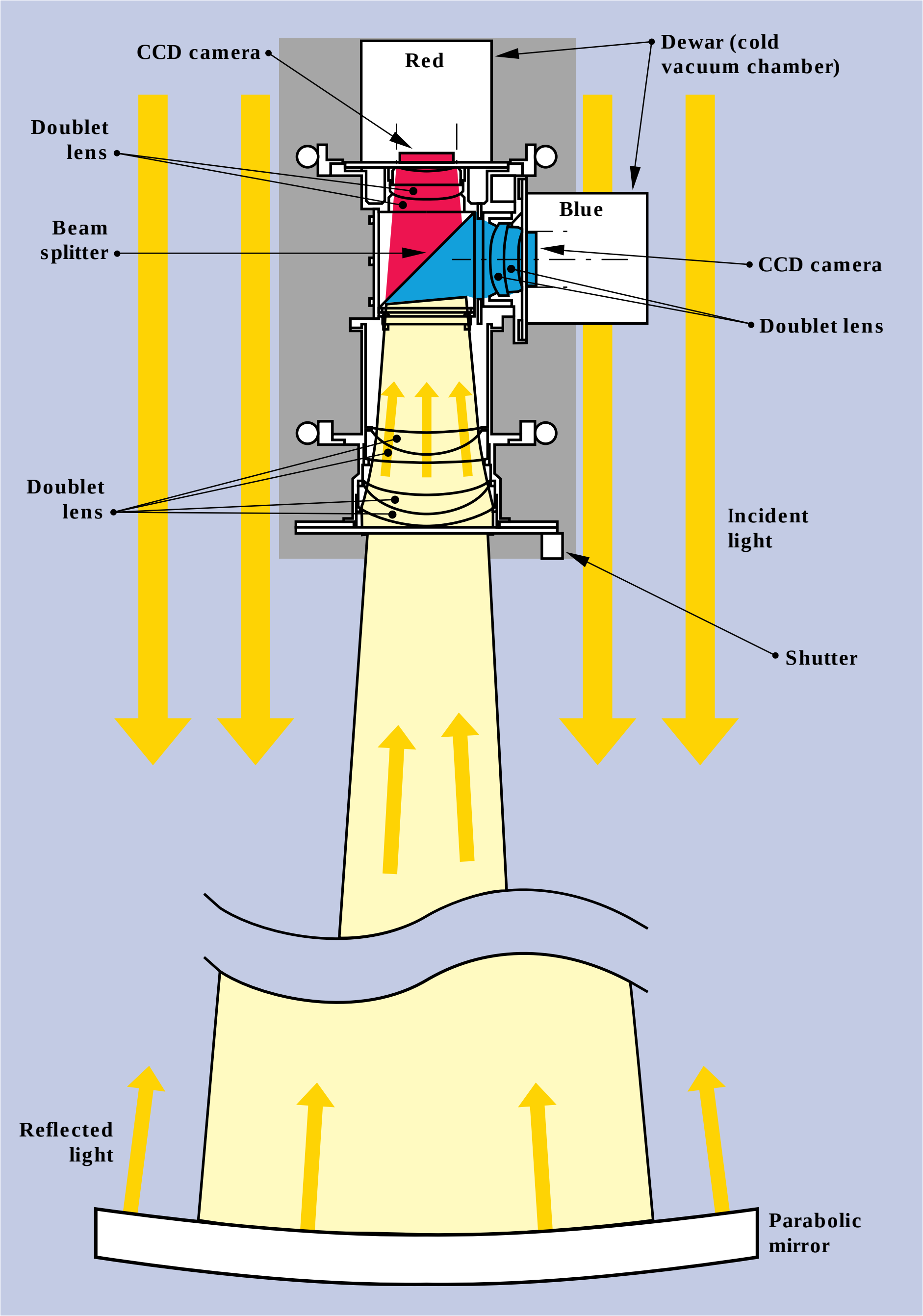


Figure 4. Dual-color, wide-field imaging system for the Mount Stromlo Telescope. Incident light from a star is reflected from the telescope's parabolic mirror (bottom) and then split into two beams—red (throughgoing) and blue (reflected)—to allow simultaneous imaging of a star in two colors. Our new optical corrector cell, shown in the gray area, was designed by E. H. Richardson (formerly from the National Research Council of Canada) and I. Z. Lewis (from LLNL) and was fabricated by OCA Applied Optics of Garden Grove, California.

corrector lenses to reduce the off-axis coma and astigmatism to acceptable levels. Coma describes the tendency of optical systems to make a point look like an asymmetrical, pear-shaped spot.

To modify the telescope, we installed new drives and encoders and moved the mirror cell back along the optical axis about 40 cm so it operated at the prime focus. We also fabricated a new optical corrector cell, shown in Figure 4. This cell gives us a useful field of view that is 1 deg in diameter, and we imaged an area about 100 times larger than that imaged by most detectors. The image quality throughout the image plane is exceptionally good.

A dichroic beam splitter, shown in Figure 4, allows us to take images simultaneously in two colors. The 450- to 630-nm spectral channel is identified as "blue" in the illustration and the 630- to 760-nm channel as "red." We use the two color channels to verify whether candidate microlensing events are achromatic (the same in all optical wavelengths). In a genuine microlensing event, the time variation in brightness is the same at different wavelengths. Such color-independent brightening would generally not be expected from intrinsic stellar variations.

Digital Cameras

Digital imaging systems are now widely used for scientific, commercial, and recreational purposes in devices ranging from ordinary video cameras to sophisticated astronomical cameras. The detector of choice for most of these applications is the charge-coupled device (CCD). Indeed, CCD detectors have virtually eliminated photographic media in many astrophysical applications, remote sensing, and the recording of time-varying events. One reason for this shift is that the quantum efficiency of photographic plates is only a few percent, whereas that for CCDs is 40 to 60%. The CCD is also well matched to the optical systems in cameras and to modern digital electronics.

The full power of this technology has not been realized because of several limitations. For one, CCDs have not been previously applied to high-resolution imaging of large fields because of low yields in manufacturing uniform, thin CCDs with large areas. In addition, the electronics, computer hardware, and software required for CCDs with very large numbers of pixels have not kept pace with other advances. We addressed and solved both problems.

Large-Format CCD Mosaics

Working with our UC collaborators, we built the two largest CCD cameras in the astronomy world. Each CCD camera contains a 2 × 2 mosaic of four 2048- × 2048-pixel CCD imagers (Figure 5) so that each array contains a total of 16 million pixels. (For comparison, a conventional television tube has only 512 × 512 or about 260,000 pixels.) The new CCDs were designed by John Geary of the Smithsonian Astrophysical Observatory and fabricated by the Loral Aerospace foundry at Newport Beach, California.

Each 15- × 15-μm pixel in our system corresponds to 0.63 × 0.63 arcsec on the sky, and each complete camera image covers half a square degree on the sky. For perspective, the Magellanic Clouds cover tens of square degrees. The CCDs are operated at cryogenic temperatures (165 K) to ensure low-noise

R&D 100 Award for the MACHO System

Each year, *R&D Magazine* recognizes the 100 most significant new products and technological innovations. At ceremonies held in Chicago on September 9, 1993, the new astronomical camera system built by LLNL and University of California researchers won an R&D 100 award.

As befits any project designed to follow more than ten million stars over several years, the number of contributors to the overall effort is large. LLNL scientists working on the project, led by physicist Charles Alcock (pictured at right with Laboratory Director John Nuckolls), are Robyn Allsman, Timothy Axelrod, David Bennett, Kem Cook, Rob Hills, and Hye-Sook Park. University of California researchers are Kim Griest, Stuart Marshall, Saul Permutter, Mark Pratt, Will Sutherland, and Christopher Stubbs. The Mount Stromlo researchers are Simon Chan, Kenneth Freeman, Bruce Peterson, Peter Quinn, and Alex Rodgers.

The MACHO camera system was recognized, in part, because of the considerable scientific importance of its current application—a definitive search for massive dark objects. Equally important, the instrument is a model for many future applications requiring rapid image-taking and processing of digital data. The system can be used for any other project in astronomy, astrophysics, and remote sensing that involves large-area surveys and the immediate processing of information. For example, Earth-crossing asteroids have the potential for catastrophic impacts with our planet. The early detection of such bodies might allow enough time to deflect them into a safe orbit. We are preparing a new camera system for this purpose.

operation. It is these arrays that are now searching for the dark matter of the universe.

Most CCDs have control and signal circuitry spaced around their periphery, which creates a good deal of dead space. Our 2 × 2 arrays, on the other hand, have no circuitry on the interior edges so that they can be butted against each other. Because our square mosaics have about 50% less dead space than other CCD arrays, they provide far more area for imaging. Our mounting scheme also allows individual CCDs within a mosaic to be replaced, if needed.

In our packaging scheme, we end up with a small gap of about 600 μm between adjacent chips. This gap corresponds to about 40 pixels. The gap is not an issue in our work because we never attempt to analyze an object that spans across two CCDs.

Electronics

The electronics we constructed for our new cameras must not only control them but must also handle the exceptionally large volume of data these cameras produce. Our electronics combine commercial and custom-made components.

We paid particular attention to isolating the instrumentation for the two imaging packages. Furthermore, since all outputs run synchronously, any output can contaminate other channels through a variety of mechanisms. We have gone to considerable lengths to control crosstalk. All communication between on-telescope camera electronics and the downstream computer system takes place over optically isolated data links. The amplified signals travel about 10 m to a signal-processing crate.

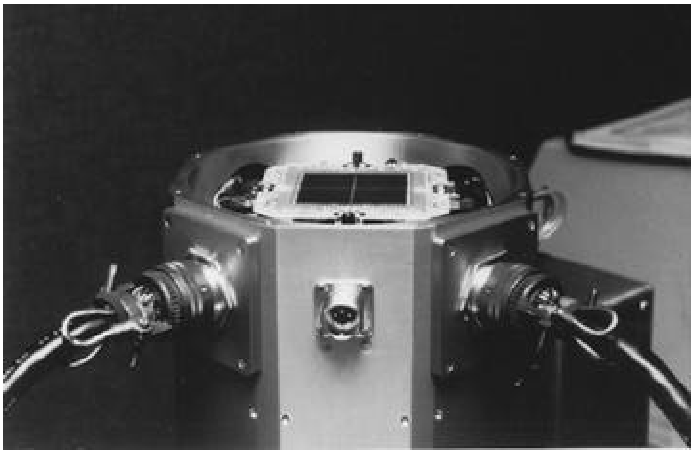
Data Analysis

Each CCD has two readout amplifiers. The 16 analog output channels (2 mosaics × 2 outputs per chip × 4 chips per mosaic) are digitized at the telescope and read out simultaneously. We use all the available amplifiers to minimize the system's readout time. It takes just over one minute to read out all the data for a frame. The digital data are fed via optical fiber cables to the control room located in the telescope's dome.

The MACHO system routinely generates one 5-min exposure of the Magellanic Clouds approximately every 6 min, reading out 32 million pixels. Each image consists of 64 Mbytes of data. The addition of important camera diagnostic information adds 20% to this volume of data. Our goal is to attain real-time processing that reduces each image to photometry while the next image is being exposed.

A multiprocessor Solbourne computer is the primary data processing system. This minicomputer controls the entire system, issues commands to the telescope, controls the camera system, manages

(a)



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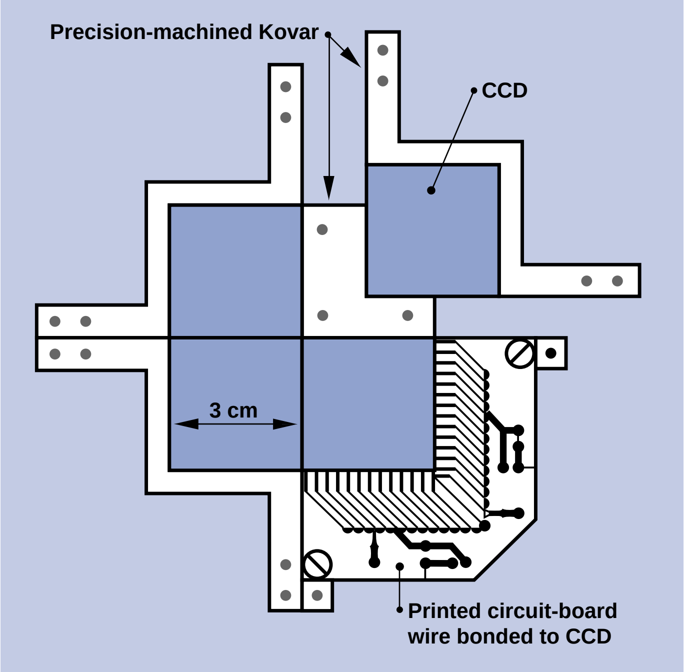


Figure 5. (a) View of one MACHO camera with the faceplate removed to show the set of four CCD imagers. The array of CCDs is 6 ¥ 6 cm. Our mounting scheme allows individual CCDs within a 2 ¥ 2 mosaic to be replaced, if needed (b).

the data flow, and archives information. The software we designed effectively manages these ongoing operations.

Images read out through the 16-channel system are written into dual-ported memory in the data-acquisition system using a custom descrambler board. Descrambling ensures that physically adjacent pixels appear in contiguous memory locations. The files are also written to 8-mm tape for archiving.

The disk-resident data are reduced with a code known as Sodophot (a point-spread, function-fitting routine for photometric analysis). First, one image of each field obtained in good seeing conditions is used to produce a template catalog of star positions and magnitudes. Bright stars in routine observation are matched with this catalog, and the catalog is transformed to the coordinate system of the observation. We then photometrically fit each template star in descending order of brightness.

When we find a star that varies significantly, it and its neighbors undergo a second iteration of fitting. The output consists of magnitudes and errors for the two color channels (red and blue) plus six additional useful parameters, including the chi-square statistic (which tests for significant differences between several samples). We use this information to flag questionable measurements that can arise from cosmic rays hitting the imagers, bad pixels, and other fake events. The dual-camera arrangement gives us a reassuring level of redundancy. For example, it is extremely unlikely that cosmic rays would cause errors on the same star at the same time in both imagers. To minimize anomalous results, we insist that a lensing signal appear with the same magnification in both colors.

An automatic time-series analysis of photometric data applies a set of filters to search for microlensing candidates and variable stars, which are abundant. The final selection process for each microlensing candidate is automatic. It incorporates criteria we established empirically using Monte Carlo addition of fake events into real light curves. These criteria include:

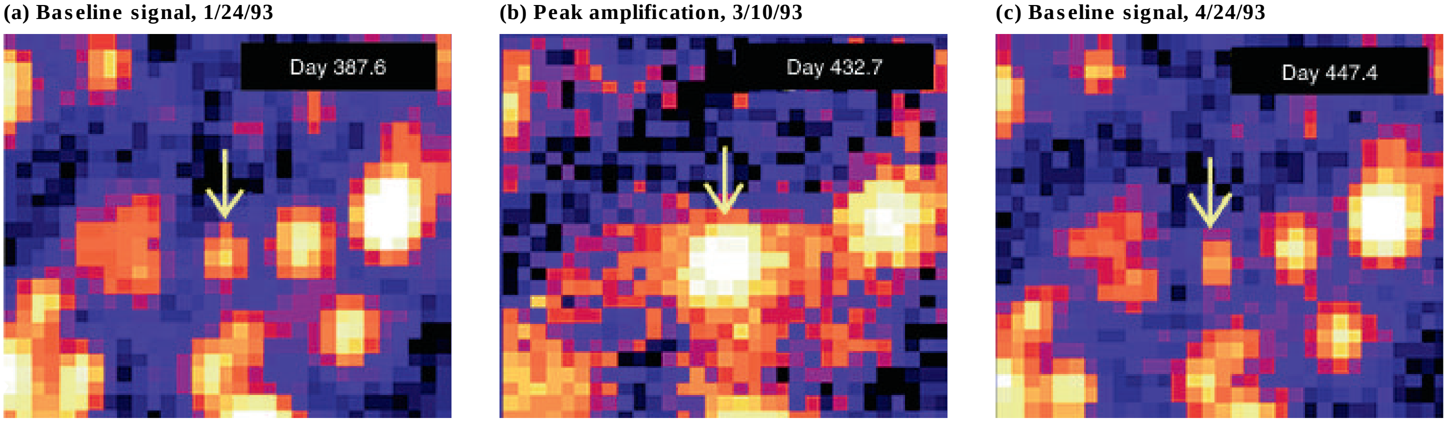
- Signal-to-noise ratio.
- Quality of fit.
- Wavelength independence of the light curve.
- Color of the star.

Results to Date and Conclusions

The MACHO project has brought to operation the most powerful survey system in the history of astronomy. On a clear night, photometric measurements on 20 to 30 million stars are possible, and we can measure twice in one night most of the stars in the Large Magellanic Cloud. More than 500,000 stars can be recorded in a single image of the dense, central region of this nearest galactic neighbor. In the first three months of operation, we recorded more photometric measurements than had previously been made in the history of astronomy. The survey will operate for a minimum of four years.

By late 1993, the American and Australian team, led by LLNL physicist Charles Alcock, had monitored about 3.3 million stars for a year. Each star was observed hundreds of times. In one remarkable event, shown in Figure 6, a star appeared to increase to 7.2 times its normal brightness and then returned to normal over a 34-day period.[2]

This event can be plotted in other ways. Figures 7a and 7b show two curves, one for the amplification of red light and one for the amplification


(a) Baseline signal, 1/24/93

(b) Peak amplification, 3/10/93

(c) Baseline signal, 4/24/93

Figure 6. Photos of our first candidate microlensing event. The peak amplification on March 10, 1993, is more than sevenfold that of the baseline amplification recorded about a month earlier and later.

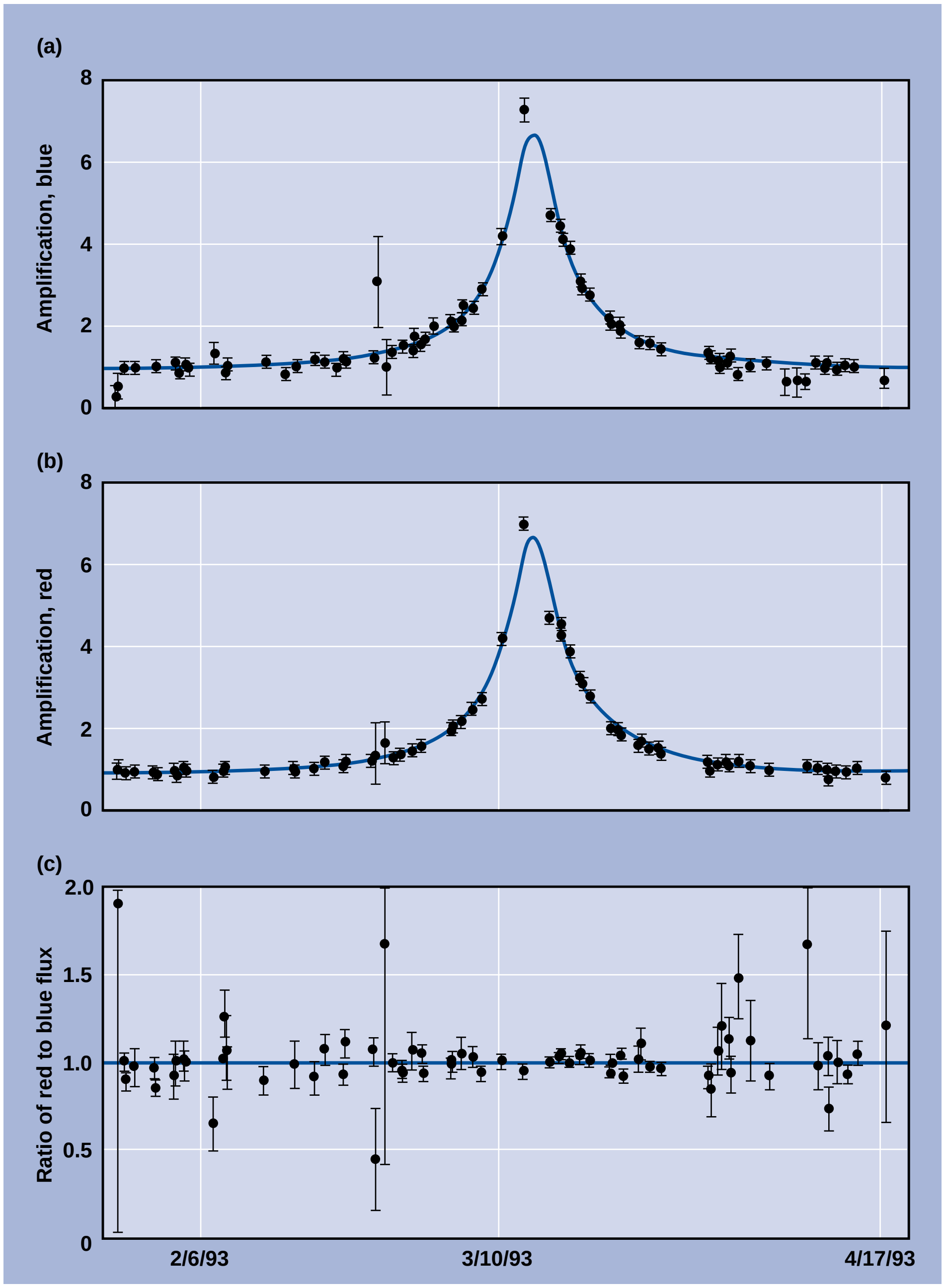


Figure 7. Observed light curve for the candidate microlensing event recorded by the MACHO camera system during February and March 1993. Amplification plotted on the ordinate is the star's flux divided by the median observed flux in the blue (a) and red (b) wavelengths. The smooth curves are the best-fit theoretical microlensing models. The peak is 7.2 times the baseline flux. The ratio of red to blue flux (c) shows that this candidate microlensing event is achromatic. (The flatness of this curve means the brightness is the same at different wavelengths.) We would not expect this kind of result from an intrinsic stellar variation, but we do expect it for a MACHO.

of blue light over time. In fact, since these two curves are essentially the same, we can speak of "the light curve for this event" as if it were a single plot. Many features of this curve are consistent with gravitational microlensing.

The light curve is *achromatic* within the error of measurement, as would be expected from a genuine event. That is, as shown in Figure 7c, the brightness does not differ at the red and blue wavelengths. The curve has the expected *symmetrical shape*, again conforming to our expectation of a true microlensing event. In addition, the event was *nonrepeating* in that this ordinary star had given no prior indication of pulsing or other activity that could account for the increased brightness. Recall that these three features are what define the MACHO signature. The finding, announced simultaneously by astrophysicists from the Laboratory and UC, could be the first evidence of dark matter in the form of MACHOs.

Recall from our earlier discussion that the duration of a microlensing event depends, in part, on the mass of the dark object serving as the lens. This means that the mass of our candidate object can be estimated (or bounded) if this is a genuine microlensing event. The estimate is necessarily a rough one because we do not know the relative velocity transverse to the line of sight or the distance to the lens. Nevertheless, by using a model of the mass and velocity distributions of halo dark matter, we find that the most likely mass for our candidate MACHO is about 0.12 that of the Sun. (Masses of 0.03 and 0.5 that of the Sun are roughly half as likely.) This mass range includes brown dwarfs and main-sequence stars. The mass range is too small to be consistent with that of neutron stars or black holes and too large to be consistent with an object as small as the planet Jupiter. It is simply too soon to say, on the basis of this single event, whether other candidates will be in the Jupiter mass range.

It is remotely possible that the stellar brightening we observed could be caused by some unknown source of intrinsic stellar variation. One crucial test for the hypothesis that we are seeing true gravitational microlensing by MACHOs is the detection of other candidates. In early 1994, we found two more potential microlensing events after an initial examination of new data. These new candidates for microlensing are not so dramatic as the first: one star appeared to increase to 1.5 times its normal brightness, and another increased to about 2 times its normal brightness. Further analysis of the data will confirm whether or not these two candidates are true microlensing events.

In this regard, it is important to note that similar observations on two other dim stars using a different technique were made by the EROS collaboration of French researchers.[3] In addition, the Optical Gravitational Lens Experiment group, which is a joint venture between American and Polish researchers headed by Paczynski, recently reported a single microlensing event using a telescope located in Chile.[4]

Whereas observing a few microlensing events is exciting because it demonstrates that our experiment is working, far-ranging conclusions are not warranted at present. We have only analyzed about 50% of our first year's data, and our observations will continue until 1996. We cannot yet say how plentiful MACHOs may be or how much of the galaxy's dark matter consists of these objects. Additional events (say, more than ten) will give us a sufficient statistical sample to allow further tests. For example, theory predicts that larger magnifications will be rarer than smaller ones. Although our results to date do not represent final answers, our findings are consistent with the idea that most—or all—of the dark matter in the universe can be considered normal rather than exotic. Moreover, our experiment is likely to be the first of the many dark-matter investigations now taking place around the world to report definitive results. We were successful because our system gathers data at a much greater rate, and we can process those data at a faster rate than other investigators.

The implications associated with verifying the existence and nature of dark matter are truly cosmic. The confirmation of compact objects will affect theories of galaxy formation and evolution. If we can account for some, but not all, of the dark matter in terms of MACHOs, then arguments for at least two different kinds of dark matter will be strengthened.

Key Words: Center for Particle Astrophysics; charge-coupled device (CCD) camera; computer code—Sodophot; dark matter; exotic matter theory; gravitational microlensing; Large Magellanic Cloud; massive compact halo objects (MACHOs); Milky Way; Mount Stromlo and Siding Spring Observatories; Optical Gravitational Lens Experiment; R&D 100 award.

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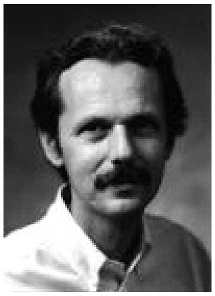

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