MACHO: Collaboration Is Key to Success

Detecting microlensing events with novel sensors, Livermore scientists discover the contents of dark matter and anticipate future searches for extrasolar objects such as earth-mass planets and large asteroids.

FROM a series of casual conversations between peers, an informal network of colleagues, and Lawrence Livermore National Laboratory's willingness to invest in high-risk/high-payoff ventures, a project to explore the very makeup of the universe was born. Results to date: the MACHO (MAssive Compact Halo Objects) project has captured a national award, is now an international effort, and has raised exciting questions concerning basic assumptions about how our galaxy—the Milky Way—and others like it are formed (see box next page).

Birth of an Idea

As an example of how an idea, a scientific "flight of fancy," can take wing and soar to unexpected heights, the search for MACHOs began almost as an offshoot of another project. Early in 1987, Livermore astrophysicist Charles Alcock, now head of the Laboratory's Institute of Geophysics and Planetary Physics, was focusing on a search for comets.

Alcock, working with Livermore physicists Tim Axelrod and Hye-Sook Park, was exploring additional ways to apply an innovative imaging technology developed for the Strategic Defense Initiative (SDI) in its search for comets at the outer edge of our solar system.

This imaging technology is based on a new class of high-resolution, wide-angle cameras, which could locate and track a large number of fast-moving objects against a cluttered background.

The camera system[1] drew heavily from the Laboratory's competency in advanced sensors and instrumentation, and it demonstrated the Laboratory's strength in integrating complex systems. The camera used charged-coupled-device (CCD) sensors—similar to those used in household video cameras—to capture digital images. This kind of imaging system, if combined with powerful parallel processing computers, could quickly produce, process, and analyze many thousands of images. Such a system would be ideal for tracking satellites—or comets, thought Alcock—in a starry night sky.

A chance conversation between Alcock and Livermore's David Bennett, then at Princeton University, led Alcock to reread a 1986 scientific paper about MACHOs written by a Princeton astrophysicist, Bohdan Paczynski.[2] In his theoretical paper, Paczynski suggested that MACHOs might be identified through a "gravitational microlensing effect." Microlensing occurs when a massive object passes between a distant star and an observatory (Figure 1). The gravitational field of the object acts as an amplifying lens, bending the star's light rays and making the star appear brighter. These events are extremely rare. At any given time, only about one star in two million is microlensed. The microlensing event can last anywhere from a few days for objects as massive as Jupiter, to weeks or even months for more massive objects.

"Rereading Paczynski's paper at this point was a remarkable experience for me," said Alcock. "I remembered reading the paper for the first time a couple years earlier and thinking it was an interesting idea and that maybe someone would find a way to do it some day. I certainly had no thought of getting into it myself. This time, while rereading, I realized that in light of the SDI technologies Lawrence Livermore had been exploring, we could almost certainly detect these microlensing events now."

Alcock did a little checking around with people in the astronomy field and discovered most people still thought that identifying microlensing events was impossible, given the existing technologies. By now, for Alcock, the idea of a comet search began to take a back seat to the intriguing possibilities of searching for MACHOs using the CCD-based imaging technology originally developed for SDI.

"We never started with an actual SDI design of something," emphasized Alcock. "We started at the whiteboard, from scratch. What this SDI technology did was convince us and others that it was possible to create a system that could produce, reduce, and interpret many thousands of digital images. This was at a time when CCDs had two contrasting uses: in television cameras, where they simply produced images,

MACHOs: Why Search for an Echo of Dark Matter

Why bother searching for MACHOs? The answer is really an answer to a larger question, one that astronomers have been puzzling for years: What is the universe made of?

For several decades, astronomical evidence has suggested that an invisible, "dark" matter surrounds and permeates the disks of our own galaxy, the Milky Way, and other spiral galaxies like it. If this dark matter were made of normal stars, dust, or gas clouds, it would be readily detected. Astronomers have determined that more than 90% of the Milky Way's mass cannot be detected with available techniques, so the unseen substance is referred to as "dark matter."

There are many theories as to what this dark matter is. One thought is that it consists of hypothetical elementary particles not yet detected, such as axions, massive neutrinos, and weakly interacting massive particles (known as WIMPs). An alternative theory is that dark matter is made up of massive objects such as neutron stars or black holes or, less exotically, brown dwarf stars 10 to 80 times the mass of Jupiter. Or, perhaps it is composed of objects similar in mass to the planet Jupiter itself. In fact, MACHO has come to be the generic term astronomers use to describe all the proposed dark, massive objects in the Milky Way's galactic halo that have not been detectable by previous means.

So, why search for MACHOs? As physicist Alcock notes, there's no question that dark matter exists. The question now is: what is it? Searching for MACHOs would provide a clue as to whether MACHOs make up some or possibly all of the dark matter.

and in astronomy, where people typically took a few images per night. This notion that you could take thousands of images with large arrays of CCDs and analyze them—that was SDI's legacy to the MACHO project." (See box, p. 9.)

The core group of Alcock, Axelrod, and Park gained a fourth member: astronomer Kem Cook. Once Cook joined the discussions, the team became very specific about system design, even to the point of having preliminary selections for CCDs, and about what the project process needed to be. "At that point," said Alcock, "it became clear to us that this was a very doable project."

Birth of a Project

In fall 1989, the MACHO project was launched in earnest with funding from Livermore's Laboratory Directed Research and Development (LDRD) Program. This program provides a way for high-risk/high-payoff projects at the Laboratory to get a fast start. But funding is only a start; the LDRD cannot cover everything.

"In the process," noted Alcock, "you get quite a bit of guidance, both from the LDRD office and from one's own directorate office as to, if you're successful, just how much funding you might get. It was beginning to look as though the project was more expensive than we could manage with just the LDRD, and it was also becoming apparent that we needed more people, more collaborators."

Looking for possible collaborators outside the Laboratory, Alcock gave a seminar on the project's hypothesis and technology at the University of California's Center for Particle Astrophysics. He did not expect one talk to generate much more than a spark of interest. At the most, he figured, it would be the first in a series that might lead to some limited collaboration in the future. However, that single seminar generated not a spark, but a firestorm of interest in the project, which led to the Center's full collaboration. Key to further progress were the Center and its sponsor, the National Science Foundation, as well as full participation from Center scientists Chris Stubbs and Kim Greist.

What Alcock did not mention was the group's breadth of planning for other contingencies. Whether or not MACHOs would be found, the growing group of collaborators set up new techniques for data analysis of light curves and for getting better information about the variations in the brightness of stars in the Milky Way and the Large Magellanic Cloud—valuable information to astrophysicists worldwide. Nonetheless, MACHOs' clues to the makeup of dark matter remained the galvanizing goal.

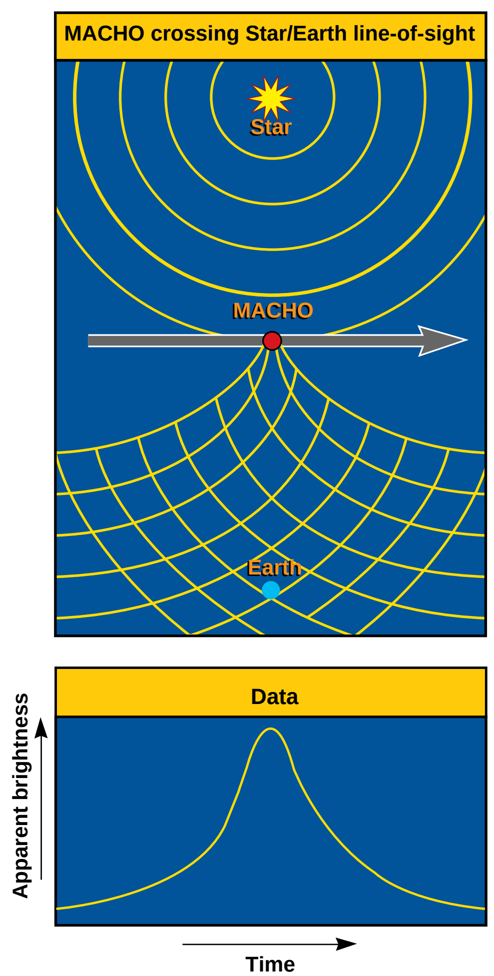

Figure 1. MACHOs passing between Earth and a star brighten the star's image to viewers on Earth by deflecting wavefronts of light coming from the star. The CCD images give information on the MACHO's relative size compared to the star.

From there, the search began for a site to build a telescope, a site that could be dedicated to the MACHO project. Included in the site requirements was the ability to view the Large Magellanic Cloud, a galaxy distant enough to exploit the gravitational microlensing effect yet close enough that individual stars could be seen using ground-based telescopes. The Magellanic Cloud, however, is only visible from the Southern Hemisphere. The site search first focused on Chile, which has the best observing conditions in the Southern Hemisphere.

What happened then is one of those miracles of serendipity, a collision of the right people in the right places at the right time. Joe Silk, a UC professor who had heard Alcock's seminar at the Center, happened to be on sabbatical at the Australian National University at the Mt. Stromlo and Siding Spring Observatories. Also at the observatories was Ken Freeman, a professor at Mt. Stromlo and Siding Spring University, who had worked with Paczynski and to whom Alcock had written about the MACHO project. Casual conversations ensued, and informal e-mail correspondence blossomed between Livermore, Mt. Stromlo, and the Center. The upshot: Mt. Stromlo and Siding Spring Observatories became a collaborator and offered to dedicate their 50-inch (1.27-m) reflecting telescope to the MACHO project for four years.

The network of collaborators has grown since those early days in 1990. Now, the project has collaborators in Munich, Germany; Oxford, England; Seattle, Washington; and San Diego, California, to mention a few. They all keep in touch and keep track of the most recent microlensing events, using the MACHO project's home page (http://www.macho.mcmaster.ca) on the World Wide Web. The Web site provides, among other things, general information about the project and "MACHO Alerts."

MACHOs Exist!

For the past two and a half years, the Great Melbourne Telescope at Mt. Stromlo has scanned the sky on clear nights, monitoring some 8.6 million stars in the Large Magellanic Cloud, searching for an echo of dark matter. The project, when viewed from its start as a "seedling" LDRD project based on SDI technology, has borne some impressive fruit.

While not directly answering the question about the composition of all dark matter, preliminary evidence indicates that MACHOs may make up over half of the dark matter. "Before we started, we expected either to find that MACHOs did not exist at all, or if they did, we expected to see about 15 events in the Large Magellanic Cloud," said Alcock. "Instead, the team has observed a total of seven microlensing events in that area since they started gathering data in 1992. Even these few events prove that MACHOs exist, and that they may make up the bulk of dark matter.[3] Most people expected that most of the dark matter would be composed of one type of thing or another—almost all MACHOs or all WIMPs, for instance.

"No one really thought it might be a bit of something and bit of something else," he said. "But that is what we are finding." Results to date are consistent with about 50% of the dark matter being MACHOs, and the rest something else.

These results have also raised questions about the models used to describe the Milky Way. "The problem has become more complicated than we expected," said Alcock. "It appears that there is much more mass in some component of the inner galaxy."

One model that has received a lot of attention is that the Milky Way is not a simple disc-like structure with spiral arms, as typically pictured, but instead a "barred" spiral galaxy, where a lot of stars exist in a bar-like structure in the inner galaxy (Figure 2).

The results also uncovered some astronomically significant "special" microlensing events, including a "binary" event, a "parallax" event, and a "proper motion" event. In the binary event, two massive objects, bound to and orbiting around each other, form the lens (see its light curve in Figure 3a). "This is spectacularly different from the simple, imperfect microlensing you get from just one MACHO," said Alcock. "Given that the majority of stars in our galaxy, unlike our sun, actually come in pairs or triplets, it should not come as a surprise to us that MACHOs might behave the same way. The binary event has great significance in a possible future project: a search for Earth-like planets outside the solar system. From our point of view, a planet going around a star is just a binary, with one object being much more massive than the other."

The parallax event is the longest microlensing event seen to date: 200 days for the object to clear the face of a distant star. The length of the event led to the need for some unusual calculations. Ordinarily, the calculations do not account for parallax, the motion of the earth around the sun. But in this case, the earth completed more than half its orbit during the event, so that motion had to be taken into account.[4] (See the light curve in Figure 3b.)

Award-winning MACHO System Scans Millions of Stars a Night

In order to effectively search for MACHOs, the collaborators had to surmount some extraordinary scientific challenges. They had to obtain an enormous number of images each night through dedicated use of a telescope in the Southern Hemisphere. And how many measurements would be enough?

"We determined that 'enough' meant exceeding the total number of photometric measurements made in the history of astronomy by two orders of magnitude—tens of millions," said Alcock.

To accomplish this task, the project required an optical imaging system with an exceptionally wide field of view and a large detector to yield an imaged area about 100 times larger than that of most telescopes.[4] Along with the high-quality, large-format CCD camera, the project needed a parallel processing system that could obtain, store, and analyze massive amounts of data—a daunting task.

The MACHO camera system includes an innovative optical system designed for the 1.27-m Australian telescope, two CCD cameras, a system to acquire and process data, and data-analysis software. This system was the first astronomical system that allowed astronomers to take images simultaneously in two colors, blue and red. The two color channels help the astronomers determine if an event is a true microlensing event. A true event will show the star brightening simultaneously at different wavelengths.

The system was the first optical imaging system to fully exploit the new generation of large-format CCD imagers. For these efforts,[1] the MACHO team in 1993 won a coveted R&D 100 Award from *R&D Magazine*. Each year, *R&D Magazine* recognizes the 100 most significant new products and technological innovations.

The project's participants believe they have seen one proper motion event. Observed in only a small fraction of all events, a proper motion event occurs when the Earth, the MACHO, and the lensed star are in almost perfect alignment. Calculations for a normal event usually assume that the distant star is a point, but in this case the team had to measure the star's diameter in terms of the size of its angle as measured from Earth, about four billionths of a degree.

Now that the project has matured, one of its most valuable results is the formation of a network of collaborators. These informal collaborators and other interested astronomers follow up on the MACHO events as they are discovered by the main telescope at Mt. Stromlo. To initially find MACHO events, the project needed the big survey instrument with its elaborate cameras and data processing system, like the one Livermore developed. However, once an event is found, a more conventional instrument can be pointed at that event and gather more information. Some of the observatories now involved are in Australia, New Zealand, Chile, South Africa, and Israel.

Surveying the Future

The core survey for MACHOs is slated to run through about the year 2000. The data acquired by then will increase the statistical accuracy of the survey. In the meantime, Alcock and others are interested in doing further astronomical exploration with the MACHO microlensing technology. According to Alcock, two strong possibilities are searching for extrasolar Earth-mass planets and searching for large asteroids on a collision course with Earth. In both cases, the network of collaborating observatories plays an important role.

For many of the MACHO events, the lenses are just low-mass stars, not very different from our Sun. If those stars have planetary systems around them, from time to time those planets should appear as a little brightening "blip" in the data, lasting a day or less. This short-term brightening is the planet's signature. Since the Mt. Stromlo telescope makes measurements only once a day, this small additional signal would not normally be detected. The collaborating network of observatories could focus their telescopes on the microlensed star, looking for such a planetary signature.

To do a meaningful search for Earth-mass planets, said Alcock, there needs to be substantial technology development—a new telescope, probably based in Chile, and a more aggressive survey for MACHOs. To locate Earth-mass planets, this new telescope would need to find on the order of 300 MACHO events a year, whereas the Great Melbourne Telescope now finds about 60 per year, most of which are in the Milky Way. A planet search would also require a more organized network capable of exquisitely sensitive measurements. The measurements made by the network would need to be very photometrically precise, better by a factor of ten than can now be done with existing telescopes.

The second possibility, searching for Earth-threatening asteroids, also seems to be a natural fit for the MACHO technology. Searching for these asteroids involves many of the same activities the MACHO project does now: surveying vast areas of sky using CCDs, analyzing the data very quickly, and scheduling other observatories to follow up on the objects that seem interesting.

A third, smaller project could be a return to the comet study that led Alcock to link SDI's technology and MACHOs in the first place. Instead of looking for stars that grow brighter due to microlensing, the researchers would be looking for stars "winking out" as a comet passes in front. This search would be yet another order of magnitude more difficult than either the search for planets or Earth-threatening asteroids, because comet events, instead of lasting days or weeks, last only a fifth of a second. "You really have to be paying very close attention," he noted. "But it can be done. It is just a question of putting it together. And that is what the Laboratory is expert at, one of its very greatest strengths."

As Alcock pointed out, Laboratory team members did not design the computers used for the MACHO project or invent the CCDs. "We used off-the-shelf computers, and we bought state-of-the-art CCDs. What we did, better than anyone else could, was integrate them. It was the first time that those very large CCDs had been used to their full potential in an integrated system. It was for that integration that we got the R&D 100 award."

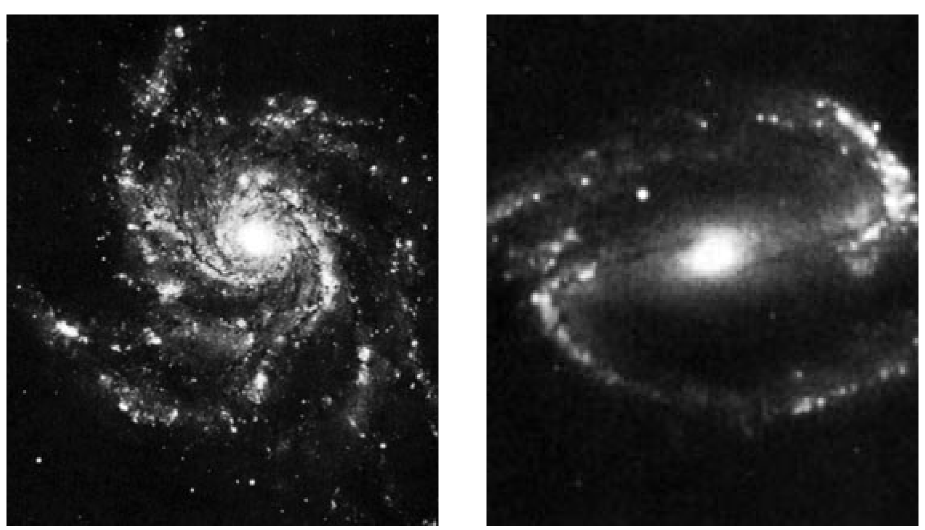

Figure 2. We usually envision the Milky Way as a spiral galaxy (left), but a spiral bar galaxy (right) may be closer to its actual configuration once the population distribution of MACHOs in the core is understood.

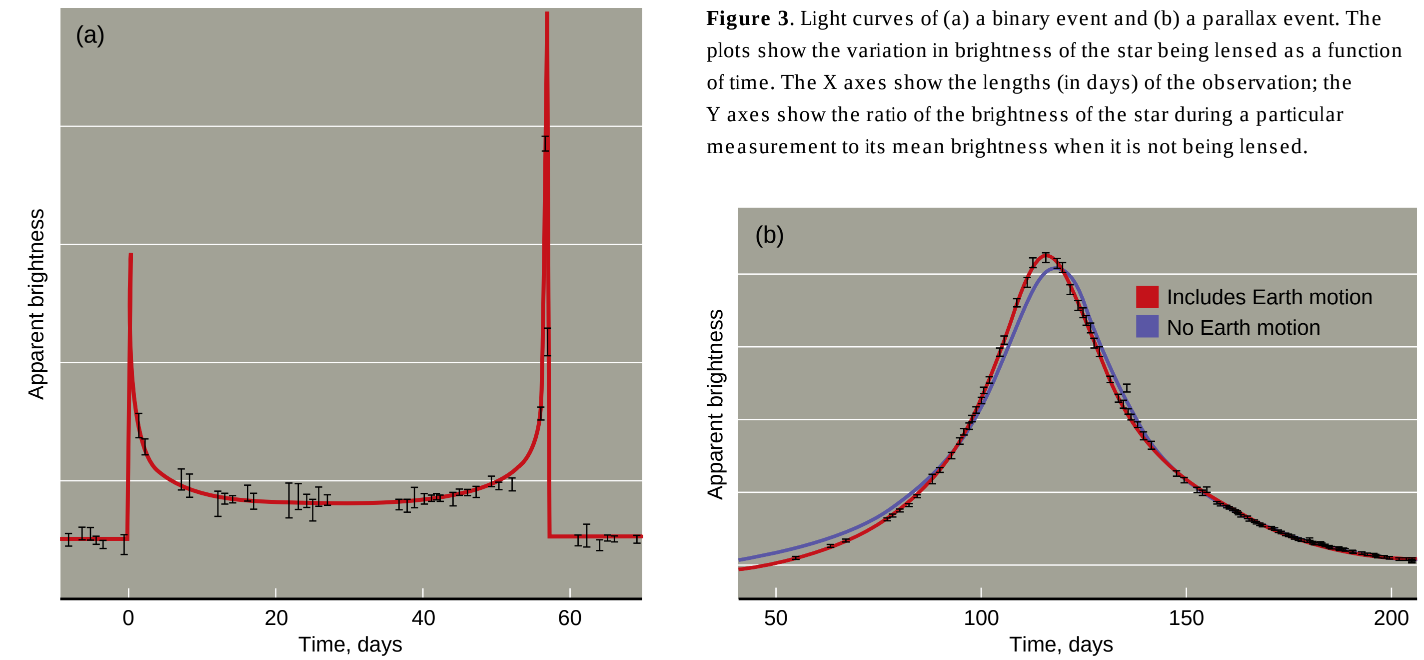

Figure 3. Light curves of (a) a binary event and (b) a parallax event. The plots show the variation in brightness of the star being lensed as a function of time. The X axes show the lengths (in days) of the observation; the Y axes show the ratio of the brightness of the star during a particular measurement to its mean brightness when it is not being lensed.

Key Words: CCD sensor, dark matter, extrasolar, light curve, MACHO, microlensing event.

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About the Scientist

CHARLES R. ALCOCK joined the Laboratory as head of its Astrophysics Center in 1986; since 1994, he has been head of the LLNL Institute of Geophysics and Planetary Physics. From 1981 to 1986, he was an Associate Professor at Massachusetts Institute of Technology, where he also received the Alfred P. Sloan Research Fellowship. From 1977 to 1981, he was a member of the Institute for Advanced Study in Princeton, New Jersey. In 1979, he held a visiting professorship at the Niels Bohr Institute in Copenhagen, Denmark, and, in 1983, was a visiting fellow at the Australian National University in Canberra, Australia. He received his Ph.D. in Astronomy and Physics in 1977 from California Institute of Technology.

Alcock's publications number about 60 in the field of astrophysics. He and fellow team members at Livermore won a prestigious R&D 100 Award in 1993 for their work on the MACHO project.