MACHO SEARCHES FIND MOST CANDIDATES IN UNEXPECTED PLACES

For two years now, three groups of astronomers and refugees from particle physics have been measuring millions of stars night after night in a stellar photometry campaign of unprecedented scale. But in fact they're not really looking for stars at all. What they seek are dark "massive compact halo objects" at least as massive as planets but generally less than a tenth the mass of the Sun. These substellar MACHOs, as they are called, would not be massive enough to ignite the fusion that makes stars shine. Heavier bodies, like neutron stars and old white dwarfs, that are dark because their stellar fuel has run out are also included under the MACHO rubric.

Such dark, compact bodies could not be seen by the various means used to detect interstellar gases. But a population of these dark objects in a spherical halo enveloping our Galaxy could be detected on the rare occasions when one of them passes close enough to our line of sight to a background star to cause discernible gravitational lensing. Given the distances and masses under consideration, the gravitational bending is too weak to produce resolvable multiple images of the spectacular kind we have seen when quasars are lensed by whole galaxies. That's why this very modest sort of gravitational lensing is called "microlensing." The observer sees nothing but the brief brightening of an otherwise stable star over a period of hours, days or weeks. (The bending precludes any occultation of the background star.)

The reason for all this effort, which depends crucially on the new technology of charge-coupled-device detectors for telescopes, is of course the dark-matter conundrum that nowadays preoccupies galactic astronomers, cosmologists and particle physicists. It's almost incontestable that stars, gas and dust account for only a small fraction of the total mass density of the universe. On local scales, for example, it's hard to understand why the outer reaches of galaxies like ours rotate as fast as they do without invoking unseen spherical galactic halos ten times heavier than the total star populations. We don't know what these dark halos might be made of, but it's widely speculated that MACHOs account for some significant fraction of their mass.

Last fall when all three groups reported their first microlensing events,[1–3] establishing the validity of this bold new technique, it looked as though we would soon learn that MACHOs do indeed surround us in abundance. But the sparsity of candidates in the months since the first euphoric reports now seems to suggest that there are fewer MACHOs in the Galaxy than one might have expected. The lack of MACHOs of planetary mass (10^{-3} to 10^{-8} solar masses) appears to be particularly convincing. The handful of microlensing events that suggest halo objects closer to the ignition mass threshold (10^{-1} solar masses) also seem to indicate a surprisingly meager population. But before they have better determinations of their search efficiencies, none of the groups is ready yet to venture a public estimate of the halo's MACHO population. Irrespective of efficiencies, however, it's already quite clear that the groups are finding a higher rate of microlensing events from the center of the Galaxy than from its outer reaches, where they were expecting to harvest the greatest catch of dark halo objects.

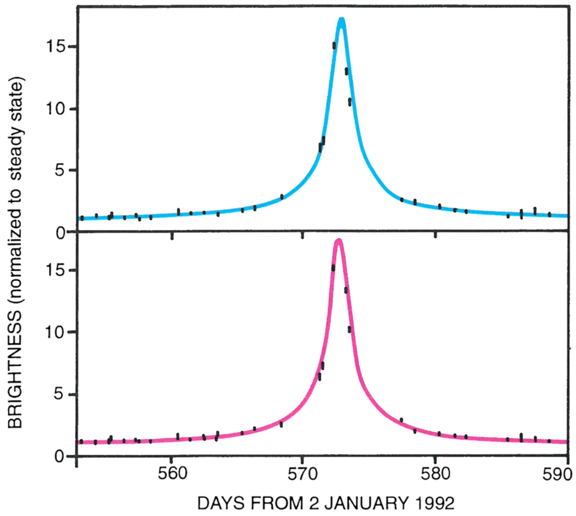
The theory of primordial nucleosynthesis in the aftermath of the Big Bang provides an estimate of the density of baryonic matter (ordinary matter made of protons and neutrons) in the universe, in terms of the observed abundances of the lightest nuclei. The conventional conclusion from this line of argument and the observed abundance of stars and gas is that most baryonic matter is dark! That provocative conclusion adds a strong impetus to the search for MACHOs.

But now a new result from a new telescope calls that conventional wisdom into question. At the 10-meter Keck Telescope in Hawaii, Antoinette Songaila (University of Hawaii) and coworkers have managed to make a measurement of deuterium abundance in a hydrogen cloud far from our Galaxy.[4] They conclude, with some caveats, that the earlier estimates of the universal deuterium abundance, based largely on measurements within the Milky Way, were too low. With this increased, but still tentative, new estimate of deuterium abundance the theory yields a *reduced* estimate of the universal density of baryonic matter, closer to what can be accounted for by stars and gas. So perhaps the argument for MACHOs becomes somewhat less compelling and the search for WIMPs (weakly interacting massive particles) and other nonbaryonic species of dark mattter proposed by the particle theorists takes on added urgency. The Hawaii group cautions, however, that its result could be a spurious consequence of the accidental interposition of hydrogen clouds along the line of sight.

Looking for MACHOs

The names of the three groups actively searching the sky for microlensing events read like a coordinated assault on political correctness: EROS, OGLE and of course MACHO. The largest of these undertakings is MACHO,[1] a collaboration of the University of California's Centers for Particle Astrophysics (at Berkeley, Santa Barbara and San Diego), the Lawrence Livermore Laboratory and the Mount Stromlo Observatory in Australia. The group has at its full-time disposal the 1.3-meter telescope on Mount Stromlo, near Canberra. The CCD detector array in the telescope's focal plane, with 32 million pixels, is the world's largest digital imaging system for astronomy.

All this imaging capacity is essential, because microlensing is so rare:



Microlensing event seen by the MACHO collaboration while looking toward the Galactic bulge last summer. Seen through blue (top) and red (bottom) filters, the background star appears to brighten to more than 17 times its normal luminosity. The duration implies a lens of roughly 0.05 solar masses. Curves are fits to gravitational lensing theory, which requires strict achromaticity.

The MACHO project's primary undertaking is to monitor discernible stars in the Large and Small Magellanic Clouds, two Southern Hemisphere minigalaxies just outside our own. The idea is to search for microlensing of these background stars due to MACHOs in our Galaxy wandering across lines of sight. When the project began, the optimistic estimate was that less than one background star in a million would be engaged in a discernable microlensing event at any one moment. Therefore one would have to keep 10 million background stars under daily surveillance.

During the course of a night's observing, the MACHO group's CCD camera covers the entire Magellanic Cloud background in 5-minute exposures of little 0.5-square-degree patches, through red and blue filters. "We record 7 gigabytes of data every night," says Christopher Stubbs (Santa Barbara). "That's like high-energy physics."

Computers scan this enormous data stream for stars in the Magellanic Clouds whose brightness appears to change from night to night. Many such stars are indeed found, but the great majority of these are either periodic variable stars or stars erupting in transient outbursts. To be taken seriously as a microlensing candidate, the star must not exhibit another brightness excursion after the one that first attracted attention, and its peak brightness must exceed its steady state by more than 50%. The latter requirement eliminates most transient-outburst phenomena, and it guarantees a reasonable search efficiency. In the most spectacular microlensing events, the background star brightens by more than an order of magnitude. (See the figure above.)

Furthermore, the star's day-to-day light curve must look the same in both colors. Intrastellar phenomena that increase a star's brightness generally affect its color. But the equivalence principle of general relativity demands that gravitational lensing be rigorously achromatic. Finally, the observed shape of the light curve must fit the theory. Variable stars generally exhibit asymmetric light curves. Microlensing theory dictates not just a symmetric light curve, but one whose precise shape is quite different from any other known astrophysical manifestation.

Duration and mass

With its nightly revisits to each background star, the MACHO experiment is insensitive to microlensing events much shorter than a week. For given distances, the duration of a lensing event increases like the square root of the lensing object's mass. If, for example, the background star is in the Large Magellanic Cloud, 160 thousand light years away, and the gravitational lens is a Jupiter-mass object at roughly half that distance in our own halo, the lensing event lasts only about three days as a lens of typical velocity traverses the line of sight. Therefore the MACHO experiment gets good light curves only for lensing objects heavier than Jupiter (10^{-3} solar masses).

The calculation that gives the duration also explains why microlensing is so rare, and why one sees only a brightening of the lensed star rather than the multiple images or "Einstein ring" of full-blown gravitational lensing: A light beam passing near a lensing object on its way here is bent significantly only if its closest approach to the lens is less than the Einstein radius R_E, which is, roughly speaking, the geometric mean between the lens's Schwarzschild radius and its distance from us. Because the Schwarzschild radius of a substellar object can't be much longer than a football field, the angle subtended by the Einstein radius of a MACHO would be less than a milli-arcsecond. That would be the angular separation of the multiple images or rings formed by this kind of lensing. It's much too small to be resolved by any optical telescope. And it demands a very precise alignment precision of background star, lens and observer that has to be quite rare. When it does happen, one sees only a transient brightening of the point source, as if a magnifying glass were passing between the observer and the background star.

The EROS group,[2] a collaboration of French astronomers and high-energy physicists led by Michel Spiro (Centre d'Etudes, Saclay), is also monitoring the entire Large Magellanic Cloud once a day in search of MACHOs heavier than Jupiter. But EROS has also undertaken to look for smaller lensing objects (down to 10^{-8} solar masses, the mass of the Moon) by monitoring one small patch of the Large Magellanic Cloud with a CCD camera once every half-hour. This rapid-sampling search for lighter MACHOs, done with a 40-cm telescope at the European Southern Observatory in the Chilean Andes, has found not a single microlensing event after surveilling 10^5 stars in that little patch for more than a year.

If the dark-halo mass deduced from the observed non-Keplerian rotation of the Milky Way consisted entirely of MACHOs of planetary mass, the EROS rapid-sampling search should have seen about a dozen lensing events by now. So the group already has an important null result, which has been reported at several conferences this year. But it has not yet been submitted to an archival journal. "That's because we don't yet know our search efficiency well enough to say at what level we can exclude MACHOs of planetary mass," explains James Rich (Saclay).

More than two years of monitoring the entire Large Magellanic Cloud daily for the longer lensing events indicative of heavier MACHOs has netted a total of only 2 clear microlensing events for EROS and 4 for MACHO. The typical duration of enhanced brightness is about a month, suggesting that the lensing masses are on the order of 0.1 solar masses, the ignition threshold. Indeed if they are above threshold, the lensing objects are likely to be red dwarf stars, whose own faint luminosty would not interfere with the observed lensing. But astronomers believe they understand the population of red dwarfs well enough to know that these very faint but legitimate stars probably can't solve the dark-matter problem. In any case, one wouldn't expect to see many red dwarfs, or stars of any kind, in the precincts of the Galactic halo along the lines of sight to the Magellanic Clouds; stars are strongly concentrated in the Galactic disk and bulge. If MACHOs, as distinguished from WIMPs or other exotic elementary particles, are the principal ingredient of the dark matter that dictates the rotation of the Galaxy, they should certainly outnumber red dwarfs as lensing objects when one looks outward toward the Magellanic Clouds, and two years of looking outward should have netted more than 6 events.

The Galactic bulge

While the MACHO and EROS telescopes were mostly looking out toward the Magellanic Clouds, OGLE[3] was using a 1-meter telescope at the Carnegie Institution's Las Campanas Observatory, in Chile, to look *inward* toward the central bulge of our Galaxy. OGLE is a collaboration of observational astronomers from Warsaw University and the Carnegie Institution of Washington DC, put together in 1992 by Bohdan Paczyński (Princeton), the theorist who first suggested that microlensing might be a good way to look for large dark objects in the Galactic halo. "Astronomers had been talking about gravitational microlensing for half a century," Paczyński told us. "But when I added the buzzword 'dark matter' in 1986, that breached the interdisciplinary barrier. High-energy physicists took note and the search for MACHOs took off."

Looking inward toward the Galactic bulge was to be a first step, a proof of principle for the new technique. Monitoring several hundred thousand prominent stars in the bulge was expected to yield a handful of microlensing events. But about half of these, according to the model calculations, would be due to lensing by red dwarfs in the inner precincts of the Galactic disk rather than by real MACHOs.

Paczyński and company got rather more than they bargained for. As of this writing, OGLE has harvested 7 microlensing events in the direction of the bulge, with durations ranging from 17 to 106 days.[5] The MACHO group finds itself with a similar embarrassment of riches. At the American Physical Society's April meeting near Washington, Stubbs announced that his group had found 4 microlensing events while looking inward toward the Galactic bulge at times when the Magellanic Clouds were too near the horizon for good seeing. "We're confused," says Stubbs. "We certainly weren't expecting to see a higher event rate in toward the bulge than when we're looking out." Both groups are seeing bulge events at about 3 times the rate they anticipated.

But perhaps those expectations have been too modest. When Paczyński visited Warsaw a few months ago, a graduate student named Marcin Kiraga convinced him that all the published predictions of microlensing by red dwarf stars in the direction of the Galactic bulge were serious underestimates. Because amplification of the backgound star's brightness is greatest when the lens is halfway between it and the observer, the published estimates considered only red dwarfs in the Galactic disk. Red dwarfs in the bulge itself, it was thought, were too close to the bright background stars in the bulge to be effective lenses. But Kiraga argues that the enormous population density of red dwarfs in the bulge could more than make up for the disadvantage of proximity. That result will soon be published.[6] "So it's very likely," Paczyński told us, "that most of our events, and most of the MACHO group's events in the direction of the bulge, are due to microlensing by faint stars rather than by truly dark matter."

Is it all red dwarfs?

What about the meager harvest of EROS and MACHO events in the direction of the Large Magellanic Cloud? The conventional estimates are tending toward the conclusion that they are too few for a Galactic halo dominated by MACHOs, but too many to be attributed to lensing by red dwarf stars in the halo.

But here, once again, the conventional wisdom is challenged by a new estimate: At the American Astronomical Society meeting in Minneapolis last month, Kailash Sahu from the Astrophysics Institute of the Canary Islands presented an argument similar to Kiraga's, but this time addressing what one should expect from red dwarfs in the direction of the Large Magellanic Cloud. It was always clear that red dwarfs in our own Galaxy would contribute very few microlensing events in that direction. But, Sahu points out, the very large density of red dwarfs in the Magellanic Cloud itself, ignored until now, should yield a significant microlensing rate. Once again, population wins out over proximity.

"That's a totally new twist," says Paczyński. "Sahu's reanalysis makes it not unreasonable to imagine that all the events seen in the direction of the Magellanic Cloud also are due to faint stars, and that no one has seen any MACHOs yet." Taking a diffent tack, Stubbs speculates that the high rate of bulge events relative to Magellanic Cloud events might indicate that the MACHO population, like the stellar population, has collapsed into a disklike distribution. But Charles Alcock (Livermore), spokesman of the MACHO collaboration, cautions that it's premature to write off a spherical halo dominated by MACHOs. "Determining our search efficiency is a difficult business," he told us. "We're not finished yet, but it's certainly less than 40%."

Where are the baryons?

The conventional primordial-nucleosynthesis argument tells us that the cosmic density of baryonic matter must be somewhere between 1% and 10% of the "critical closure density" strongly favored by the inflationary Big Bang scenario. Traditionally the primary uncertainty in that estimate has been ascribed to our ignorance of the precise value of the Hubble constant. But now the Hawaii group's new measurement of deuterium abundance outside the Galaxy[4] has introduced a new uncertainty into the primordial-nucleosynthesis scenario. Visible baryonic matter accounts for perhaps 0.3% of the closure density. If the total baryonic density exceeds that by an order of magnitude, MACHOs become very plausible. But if the new deuterium measurement holds up, reducing the theoretical lower limit of cosmic baryon abundance to something like 0.5% of closure, it may become unnecessary to invoke *dark* baryonic matter.

With or without MACHOs, the Galactic rotation data demand a dark halo an order of magnitude more massive than all the stars in the Milky Way. Nonbaryonic halo particles, it is assumed, would not coalesce into macroscopic celestial bodies. Nor would they suffer the dissipative interactions that eventually collapse a spherical distribution into a spinning disk. That's because these as-yet-unknown particles are presumed to have no electromagnetic interactions.

Particle theorists have come up with two particularly attractive candidates: supersymmetric "neutralinos," the classic WIMPs, several orders of magnitude heavier than the proton, and axions, ten billion times lighter than the electron. Both were hypothesized for purely particle theoretic reasons. But the theories happen to predict that production of such particles in the Big Bang would have left us relic abundances that are just about what the cosmologists want for closure. Furthermore, either population would nowadays have the "cold" velocity distribution favored for explaining the evolution of large-scale structure. "It's either the Grand Cosmological Hint," says University of Chicago cosmologist Michael Turner, "or the Grand Misdirection."

The meager harvest of halo microlensing candidates thus far, Turner argues, lends impetus to the the search for WIMPs and axions. But even a high MACHO event rate, he points out, would not impose a very restrictive constraint on the abundance of nonbaryonic dark matter in the Galaxy.[7] "In any case," says Turner, "I suspect we're going to learn a lot about our Galaxy from microlensing."

—BERTRAM SCHWARZSCHILD

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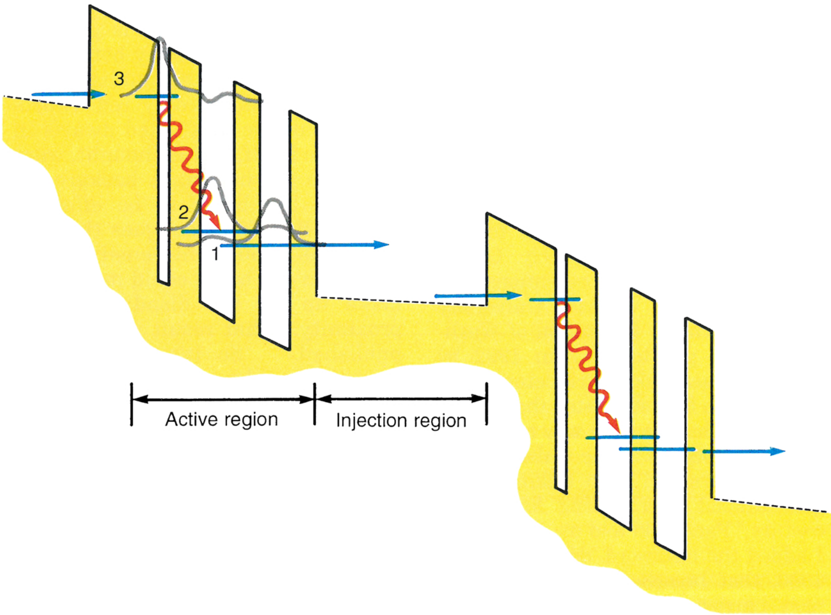
INFRARED LASER DEMONSTRATES A NEW PRINCIPLE OF OPERATION

In conventional semiconductor lasers, the photons come from the recombination of electrons and holes. But in a new semiconductor laser recently unveiled by a team at AT&T Bell Labs,[1] the photons are emitted as electrons cascade from one energy level down to another in a staircase-like arrangement of quantum wells. The new laser is thus unipolar, relying only on electrons rather than on both positive and negative charges. While the physics of this "quantum cascade laser" is very exciting, its commercial potential is not. The threshold current is still very high and might limit its practicality. However, the laser could be used as a research tool and should certainly stimulate still more innovations in design.

The new laser, which operates at 4.25 microns, doesn't have a lot of competition in its wavelength region, the mid- to far infrared. In conventional diode lasers, the bandgap of the material in the active region determines the wavelength, because the photons carry the energy released as an electron from the conduction band combines with a hole from the valence band. But the semiconductors with small enough bandgaps to produce infrared photons are hard to process and sensitive to temperature. The beauty of the quantum cascade laser is that the wavelength is independent of the bandgaps of the materials. The laser can therefore be made of well-behaved and well-understood materials, with the design tailored to produce the desired wavelength. Other considerations, however, may limit the quantum cascade laser to wavelengths longer than the near-infrared region (1.3–1.55 microns) now used for optical communication.

The laser was built by Jerome Faist, Federico Capasso, Deborah Sivco, Carlo Sirtori, Albert Hutchinson and Alfred Cho, all of Bell Labs in Murray Hill, New Jersey. This group is in the midst of making a companion laser at 10 μm. Like the 4.25-μm device, it is designed to lase in an atmospheric window, that is, a wavelength region where the radiation absorption by atmospheric gases is small. These lasers might prove useful in monitoring of atmospheric pollution. Other potential applications include free-space point-to-point communications and collision-avoidance radar for automobiles.



Quantum cascade laser is made from a series of 25 active regions separated by regions where the bandgap is uniformly graded. Radiation (red arrow) is produced when an electron (blue arrow) tunnels from the $n = 3$ energy level into the $n = 2$ level. From there the electron tunnels to level $n = 1$ and out to the graded region (dotted lines), where the electron cools to a lower energy level. It is then ready for injection by tunneling into the next active region. Gray curves show the wavefunctions at three energy levels. (Adapted from ref. 1.)

The active regions

The energy staircase down which each electron travels is really like 25 short flights of steps, each separated by a landing. Each flight—the laser's active region—consists of three coupled quantum wells, as diagrammed in the figure above. An electron from one landing—the injection region—tunnels through the first barrier into energy level E_3, centered in the narrowest well. As the electron then jumps to level E_2, centered in the neighboring well, it emits