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EMAIL: beamline@slac.stanford.edu
FAX: (650) 926-4500

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Cover: The Large Magellanic Cloud, a satellite of our own Galaxy, is visible to the naked eye from the Southern Hemisphere. This observation was made by the 4-meter Blanco telescope at Cerro Tololo InterAmerican Observatory in Chile. Astrophysicists watch millions of stars in the Large Magellanic Cloud for a handful of telltale brightenings, which signal gravitational lensing of the starlight by a dark foreground object, or MACHO. See Kim Griest's article on page 8. (Courtesy National Optical Astronomy Observatories)

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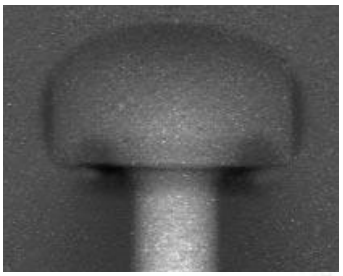
FEATURES



Proton Radiograp

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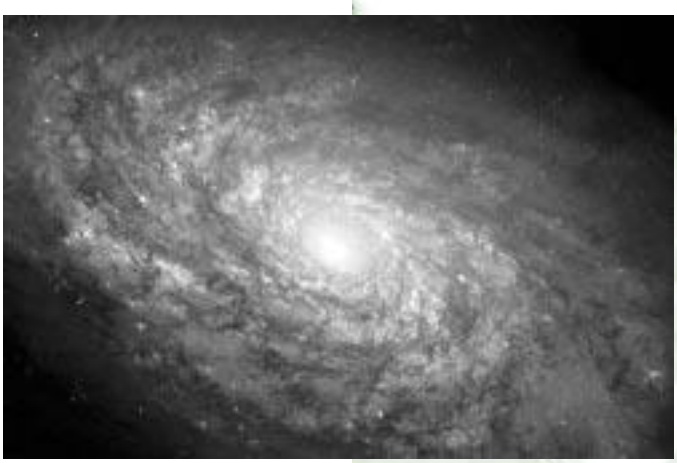

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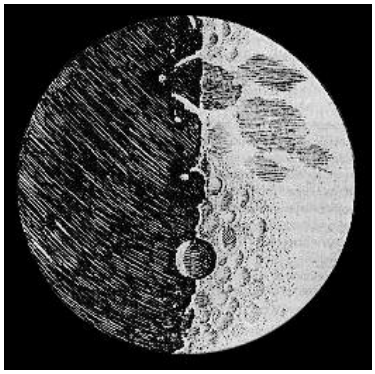
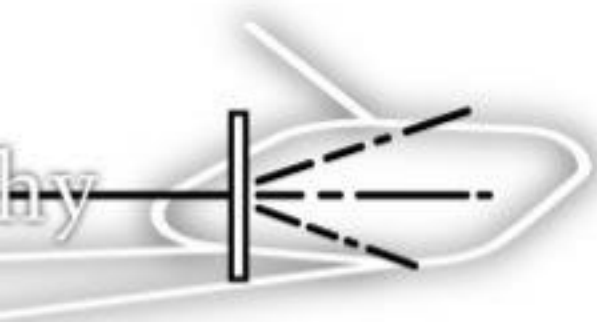




FOREWORD

The New Economy Model Universe

GEORGE SMOOT

SOMETIMES NEW IDEAS are quickly accepted—for example, X rays for radiography of opaque objects, such as humans. Others take much longer—for example, using protons for radiography. The article "Proton Radiography" by Edward Hartouni and Christopher Morris points out that the idea of proton radiography has been around for half a century but is only now being seriously developed for routine use, especially for rapidly evolving systems. The key was the realization that standard particle physics techniques could be applied fruitfully. Acceptance of a new concept has to do both with how useful the new idea is and how it impends upon our cherished or familiar notions. People have been remarkably resistant to new models of the Universe—just ask Galileo!

The article "The Stained and Spotty Heavens" by Virginia Trimble reviews some of the long historical development of the idea that the heavens are not ideal. This idea in turn supports the concept that the Universe is made of ordinary materials and that the laws of physics, particularly Newton's universal gravitation, apply to the heavens. These imperfections and the laws of physics provide much of our key astronomical information.

With emerging confidence in Newtonian gravitation, astronomers came to understand the need for dark matter. The modern beginning dates to a suggestion from Fritz Zwicky in 1932. It strengthened over years as the observational evidence improved. Assuming that stars move in the gravitational potential caused by the accumulated matter of a galaxy, the stars' kinetic energy matches their gravitational potential energy. However, if the observed stars have roughly the same mass-to-light ratio as our Sun, then the stars' velocities require about ten times as much matter as observed by their light. Traditional astronomers assumed that matter would be standard and dark in the sense that it did not radiate or reflect significant light. Interloper particle

physicists, turned astrophysicists and cosmologists, speculated that this dark matter might be new particles. Theorists quickly recognized that weakly interacting particles, if massive, would have roughly the right abundance as relics of the Big Bang to account for the needed dark matter. Hence we have the acronym WIMPs from Weakly Interacting Massive Particles. Kim Griest then produced the counter point acronym MACHOs (Massive Astrophysical Compact Halo Objects) as a baryonic response to WIMPs.

Natural extensions of particle physics techniques provide appropriate means to detect WIMPs. Einsteinian gravitation provides a means to search for MACHOs, provided one is willing, as in high-energy physics, to observe and process millions of events to find the very few that show the MACHOs. In this issue of the *Beam Line* are two articles about experiments exploring for dark matter: "All about MACHOs" by Kim Griest and "Hunting for WIMPs" by Anthony Spadafora.

George Smoot, a member of the Beam Line *Editorial Advisory Board, is an astrophysicist and cosmologist at the University of California, Berkeley, and Lawrence Berkeley National Laboratory. His research on the cosmic background radiation, thought to be the relic of the intense heat of the early Big Bang, led to his role as head of the group that developed the Differential Microwave Radiometer for NASA's COBE satellite.*

When these dark matter experiments were launched, the motivations and context were much less developed than at present; 'modern' cosmologists thought that the Standard Model of the Universe involved cold dark matter. More traditional astronomers thought that the Universe was WYSIWYG (what you see is what you get)—the Universe needed only known and familiar particles. Many astronomers would have preferred a Universe in which everything was visible, but, if something was going to be dark, then it should be good, old, stable baryons.

The searches for WIMPs and MACHOs were competing experiments and competing world views. Arguments continued as the experiments developed. Studies of large clusters of galaxies—regions large enough to be thought of as a "fair sample" of the Universe—indicate that the total gravitational potential was large but well below the critical value that would produce a geometrically flat Universe, one considered to be the dividing line between a

Universe that would expand forever and one that would eventually collapse. If the critical density were exceeded, the Universe would eventually stop expanding and recollapse. Arguments went on about whether baryons could not only explain the rotation curves of galaxies but also even the full content of the Universe, which would have an open geometry fated to expand forever and slowing its expansion only moderately. Cosmologists working on the formation of galaxies, clusters, and general large-scale structure found that they needed the cold dark matter (CDM); baryons alone were not sufficient. Though neither model fitted all the data well, the models could be stretched thereby keeping the controversy on the nature of the dominant matter alive.

During the years these dark matter searches developed, our picture of the Universe underwent a significant change, especially recently. We still rely confidently on gravity (specifically general relativity) and the concept that the laws of physics can be applied throughout the Universe. Supernova and cosmic microwave background (CMB) observations have advanced our understanding substantially.

Observations of type Ia Supernovae (see "The Fate of the Universe" by Gerson and Judith Goldhaber in the Fall 1997 issue of the *Beam Line*, Vol. 27, No. 3) have indicated that the universal expansion is accelerating. The Universe is expanding more quickly at present than it was in the past. If the Universe were dominated by dark matter, then its expansion would be slowing under its relentless gravitational drag. Instead, the rate of expansion is increasing, indicating that the dynamics of the Universe must be dominated by some form of energy that is tied to the structure of space, such as a vacuum energy density.

There are many potential candidates for this dark energy, including scalar fields and frustrated networks of topological defects

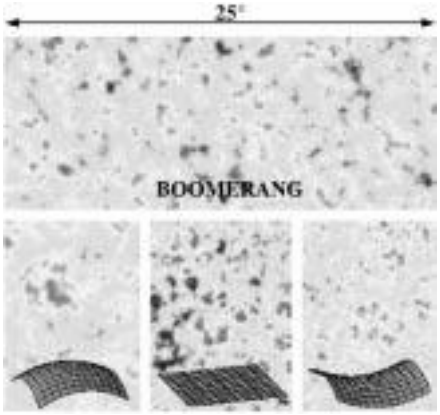
For Further Information

MAXIMA: http://cfpa.berkeley.edu/group/cmb/index.html
BOOMERANG: http://www.physics.ucsb.edu/~boomerang/
SMOOT: http://aether.lbl.gov/
SUPERNOVA: http://panisse.lbl.gov:80/public/
CDMS: http://cdms.berkeley.edu/
MACHOS: http://wwwmacho.mcmaster.ca/
Connection to all: http://cfpa.berkeley.edu/

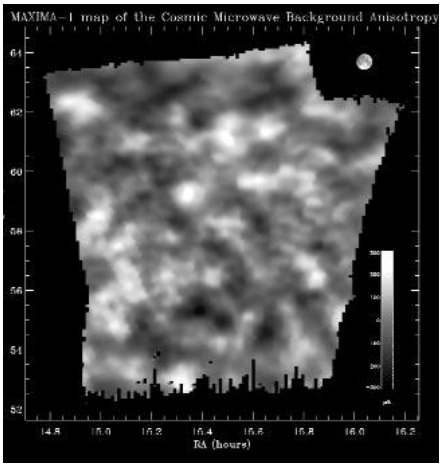
from spontaneous symmetry breaking. Different forms of this energy can have different behavior. The key feature is that the pressure from this dark energy be more negative than one third of its density in order to make the expansion accelerate. The more dark matter contributes to the energy density of the Universe, the more negative the pressure of this dark energy must be to produce accelerating expansion. Vacuum energy, or equivalently a cosmological constant, would have the pressure negative with amplitude equal to its energy density. Currently, cosmologists use the cosmological constant as a convenient parameter to stand for and characterize this spatial energy. The investigation of this dark energy is one of the key questions of cosmology and particle physics. [Editor's Note: for an explanation of the physics and pressure of the vacuum energy density (false vacuum), see the article "Was Cosmic Inflation the 'Bang' of the Big Bang?" by Alan Guth in the Fall 1997 issue of the *Beam Line*, Vol. 27, No. 3.]

After the Griest and Spadafora articles were submitted to the *Beam Line*, new CMB observations were made public. The balloon-borne experiments BOOMERANG and MAXIMA (see the sky maps on the right), combined with the COBE differential microwave radiometer (DMR) data, provide a large step in precision of CMB observations and give strong evidence for a nearly flat geometry for the Universe.

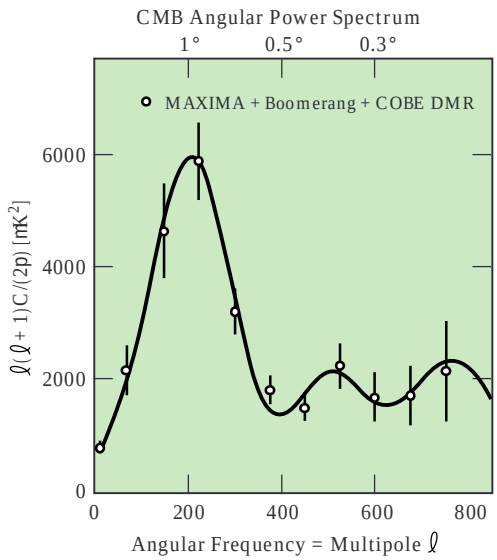
The fluctuation level as a function of angular size is quantified in the CMB angular power spectrum shown on the next page. These CMB data show a convincing, well-defined peak in the angular power spectrum at the expected scale of about one degree ($\ell \sim 200$). This is strong evidence that primordial density perturbations were produced very early and that these perturbations grew, under the influence of gravity, to produce



The upper panel shows a central section of the large BOOMERANG map of the CMB. The lower panels show CMB maps generated from theoretical models of a closed, flat, and open universes. The key point is the angular scale on which the features appear.



This MAXIMA sky map represents a slice of the sky some 22 times the size of the moon or about 500 times its area. What is most evident are the structures roughly twice the size of the moon or about 1 degree in linear extent. The moon, which is 1/2 degree on our sky, is included for scale. Astrophysicists were surprised at the paucity of moon and smaller-sized structures.



The combined MAXIMA, BOOMERANG, and COBE differential microwave radiometer cosmic microwave background anisotropy angular power spectrum shown as data points and error estimates. The smooth curve is the best fitted inflationary model flat Universe power spectrum.

the large scale structure present in the Universe today. Augmenting the Big Bang model with inflation is the only model that is supported by these data.

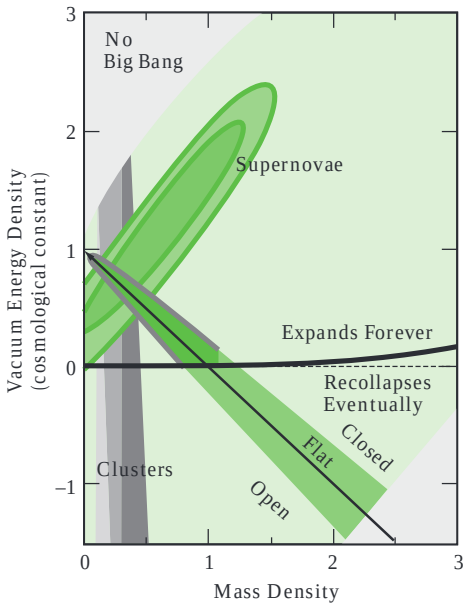
The CMB data also show more—a relatively high first peak in the angular power spectrum and a relatively low second peak. A universe with significant dark energy (for example, cosmological constant) and a lesser amount of cold dark matter has a much higher first peak to second peak ratio than one with only cold dark matter. A more effective way to lower the second peak is to add in extra baryons (uh-oh, here we go again?) over the Big Bang light element nucleosynthesis estimate of about 4 percent of the critical density. Fits to the CMB data give numbers of order 6±2 percent with a 95 percent confidence level of the critical density. This potential disagreement is very interesting but should not obscure the remarkable point that two very independent methods and underlying physics effects give roughly the same answer for the baryon density in the Universe.

The illustration on the next page shows the likelihood contours in the vacuum energy density versus matter energy density plane for the clusters, supernova Ia, and CMB data. Note the area of overlap with a matter component around 30 percent, a cosmological constant or dark energy about 70 percent, and a baryon density of around 5 percent. The other cosmological parameters, such as baryon density, are suppressed in this figure. If the plot were three dimensional, the overlap would produce likelihood ellipsoids to its energy density, total matter, and baryon densities.

We have thus extended the idea that there can be not only non-baryonic matter but also that there can be significant energy in the Universe that is

not matter or relativistic particles, such as photons and neutrinos. We have extended the Copernican Principle—not only are we not the center of the solar system nor are we made of the dominant form of matter, but even that matter is not the dominant form of energy. We have resurrected the "Flat Universe Society." Thus the context, but not the significance of dark matter searches and their results, have changed substantially over time. The discovery of MACHOs is a major accomplishment as is the determination of their abundance. There are tantalizing results from the WIMP searches, and we eagerly await new results.

While we have begun to answer some questions, new ones have arisen to take their place. Some were questions we did not know to ask, and others have risen in import. These new questions and results underline the merging of cosmology and particle physics and the connections between them.



Likelihood contours in the vacuum energy density versus matter density plane for the cluster, supernova, and cosmic microwave background data sets. Note that there is a region of agreement.

All About MACHO

by KIM GRIEST

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

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

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

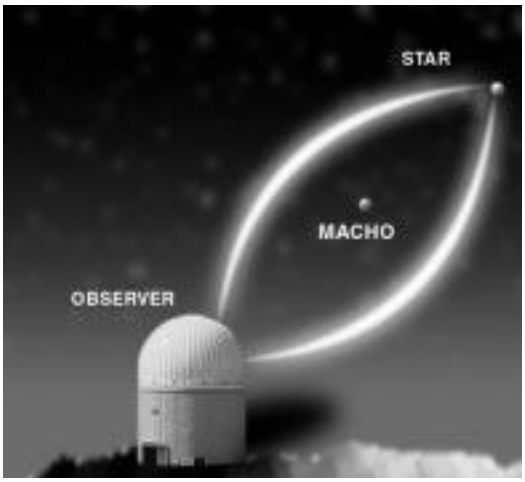
S

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

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

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

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



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

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

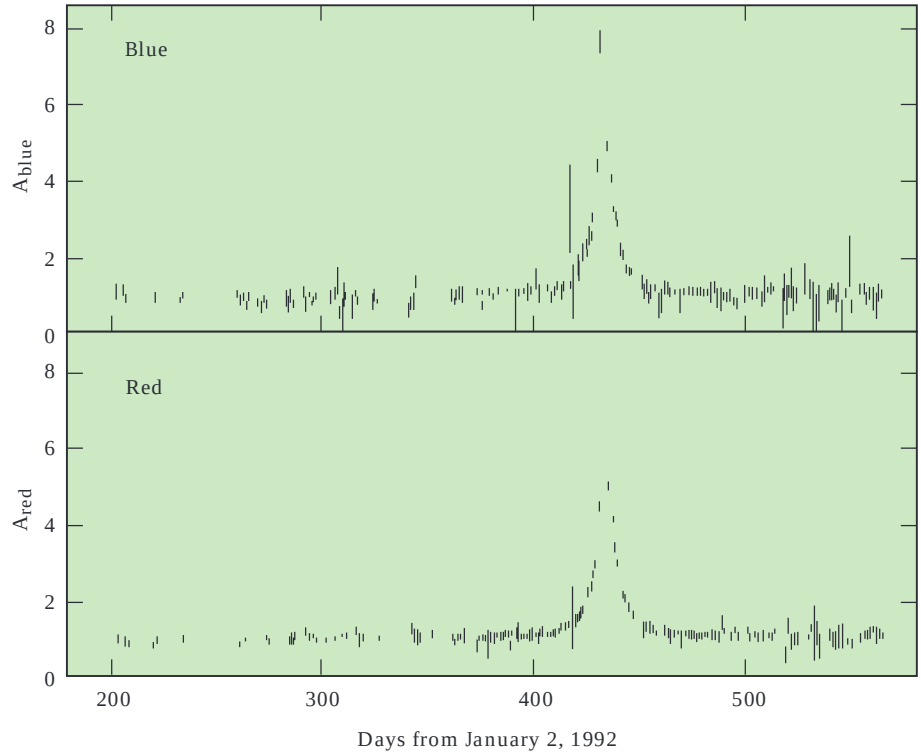
For the astronomical candidates MACHOs, the situation changed in 1986 when Bodhan Paczynski suggested a method of detecting any compact object that might make up the dark matter in our Galaxy. Starting in 1989, this idea gave rise to several experiments, culminating in 1993 with their discovery!

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

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

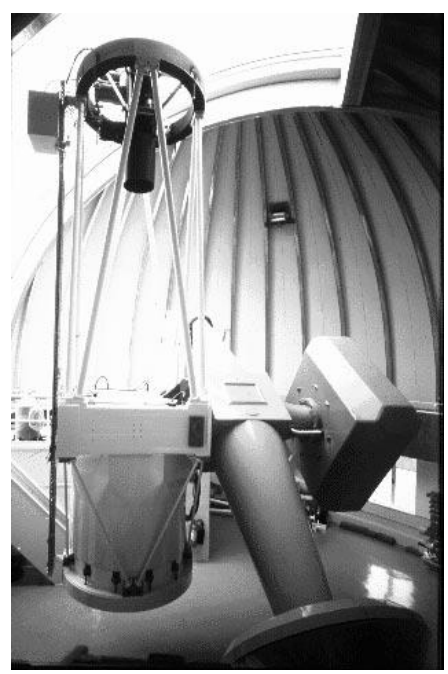
should be trillions of MACHOs moving at speeds near 300 km/sec through the halo. As the Earth, source star, and MACHO move into and out of alignment, the source star appears to brighten, then goes back to its normal brightness, in a time-symmetric and very specific unique way. One can calculate the probability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

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

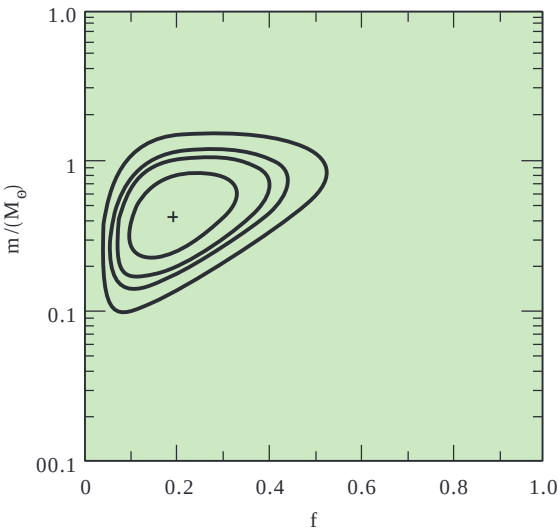


A microlensing event discovered by the MACHO collaboration in 1993. Brightness of the star is plotted against time in two different band passes.

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



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



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

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

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

Next, it is not an easy task to calibrate the experiment. There are rainy days, telescope glitches, bad seeing, full moons, and so forth which mean that the experiment is not equally sensitive to all the microlensing that occurs. In addition, the sampling of each star is not constant, and light curves that are assumed to consist of the light from one star, may in fact be "blends" of several stars that happen to be near each other on the sky. As the quality of the atmosphere changes, the amount of blending will vary with time, giving unequal quality brightness measurements. Thus, it is a major task to understand how many microlensing events one would expect to see, even if the Milky Way halo consisted entirely of MACHOs. A major effort involving creation of artificial images under different conditions and Monte Carlo of the effects of all the above errors was undertaken, and the efficiency of the experiment calculated. This efficiency ranges from around 10 percent for events that last 10 days, to 50 percent for events of duration 200 days, to below 5 percent for events of duration 1000 days. Using this efficiency curve, one can do a proper comparison of the number of microlensing events expected and the number of microlensing events observed.

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

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

Microlensing aficionados usually quote results using the "optical depth" to microlensing. This is the probability than a given star is undergoing microlensing at any given time. A full MACHO halo predicts an optical depth towards the Large Magellanic Cloud of about 5×10^{-7}. The result of the above analysis gives a measured optical depth of $1.2^{+0.4}_{-0.3} \times 10^{-7}$, quite consistent with the likelihood analysis.

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

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

We also note that the measurement that 20 percent of the Milky Way dark matter consists of MACHOs requires several caveats. For example, it has been suggested that the Large Magellanic Cloud itself contains a large extended population of faint stars. Such objects have not been detected, but also have not been ruled out. If they exist, the microlensing observed by the experiments may be due to "Large Magellanic Cloud self-lensing" rather than MACHOs moving in the dark halo of the Milky Way. Thus, in fact, the MACHO contribution to the Milky Way dark matter may be zero! However, this question has not been settled, and at this point a 20 percent MACHO halo is a reasonable hypothesis.

How will this question be settled? A main problem in current microlensing experiments is that they are incapable of determining the distance of the lens object. If Large Magellanic Cloud self-lensing is responsible for the observed microlensing events, then the lenses should all be at about 50 kpc, the distance of the Large Magellanic Cloud. If halo MACHOs are responsible, the typical lens distance should be around 10 kpc. Thus even a few determinations of lens distances would solve the problem. Fortunately there are several ways that new microlensing experiments could determine these distances. For example, the Space Interferometry Mission is capable of measuring the parallax of the lens and obtaining the lens distance. Other satellite or ground-based monitoring efforts may be able to determine parallaxes for certain classes of microlensing events. In addition, a certain fraction of microlensing events are "exotic" in that the light curve shape is modified by effects such as a binary lens, or the finite size of the source star. In such cases, it is sometimes possible to determine the lens distance. One such binary event was seen towards the Small Magellanic Cloud (SMC), and the lens was determined not to be a member of the dark halo, but to be a SMC star lensing another SMC star. The Small Magellanic Cloud is known to be quite extended along the line-of-sight, so it was not surprising that the one measured event was SMC self-lensing. However, even one such event towards the Large Magellanic Cloud, which is not known to be extended, would be most valuable in settling the question of where the Large Magellanic Cloud lenses are located.

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

Hunting for WIMP

by ANTHONY L. SPADAFORA

SINCE THE DAWN of the Copernican revolution some four hundred and fifty years ago, modern science has progressively shown that our Earth does not occupy a privileged location at the center of the Universe. We orbit a rather ordinary star that, along with hundreds of billions of other stars, is a member of a spiral galaxy, of which there are likewise billions of others. Current work in cosmology proposes yet a further step in this revolution: we, and the known world around us, are not even made of the form of matter that comprises the bulk of the Universe! This bold hypothesis – that there is a vast amount of dark matter in the form of a flux of a new type of elementary particle—is now being put to the test in a number of deep underground laboratories.

For over 70 years, it has been realized that astronomical observations indicate that perhaps as much as 90 percent of the mass of the Universe is dark (does not emit or absorb light or other forms of electromagnetic radiation), but makes its presence known only by its gravitational effects. A number of different approaches to understanding the nature and the amount of dark matter are currently being pursued, and this has become a very active area of research. While much progress has been made in the past few years, we are clearly facing a challenging problem as we know neither the kind nor the amount of the matter we are looking for. Yet, clever experimental techniques have been devised and with their improved sensitivities and progressively longer running periods are starting to elucidate the problem.

DETERMINING THE AVERAGE DENSITY of matter in the Universe is a main effort in contemporary observational cosmology. Knowing how much matter exists is essential if we are to understand how galaxies and their marvelous large scale pattern of clusters formed. The mass density is also a key parameter in

S Underground

understanding how the Universe as a whole evolved and what its ultimate fate will be—continued expansion or a collapse in a "Big Crunch."

Since the 1930s, astronomers have been faced with the dark matter conundrum: the matter we see—stars, gas, dust—can only account for a tiny percent of what we believe to be the total mass of the Universe. The average density of matter is now thought to be dominated by some other, invisible component. One approach to this problem is to search for astrophysical objects that fail to radiate light (see the article by Kim Griest on page 8). However, through the modern particle physics-cosmology connection, they do not appear to explain the bulk of dark matter, and some other form of matter is needed.

Theorists believe they understand very well how the hydrogen and helium that comprise over 99 percent of the atoms of the stars we see were formed in the Big Bang. They can predict with considerable accuracy how much deuterium (a rare isotope of hydrogen) should also have been formed. Combining theory with recent precise measurements of this cosmic deuterium abundance, cosmologists can put tight constraints on how much of the dark matter can be made of ordinary matter (that is, made of quarks and leptons). These constraints lead us to the startling conclusion that most dark matter must be made of some yet undiscovered type of elementary particle.

Theorists, ever imaginative, have proposed many possible candidates for this new form of dark matter, the so-called "non-baryonic" component. One of the leading ideas is that it is in the form of WIMPs, or Weakly Interacting Massive Particles. These are neutral particles, roughly about a hundred times more massive than a proton, that interact only very weakly with ordinary matter. They were produced in the Big Bang, and as the Universe expanded their density decreased to a low level. They are left as a relic flux throughout

The CDMS Collaboration

Case Western Reserve University
Fermi National Accelerator Laboratory
Lawrence Berkeley National Laboratory
National Institute of Standards and Technology
Princeton University
Santa Clara University
Stanford University
University of California, Berkeley
University of California, Santa Barbara
University of Colorado, Denver

space and are thought to have accreted to form the dark "halos" of galaxies such as our own Milky Way.

When particle theorists were asked what kind of elementary particle a WIMP could be, they were quick to realize that the hypothetical "neutralino" fits the bill. These are neutral superpartners of Standard Model particles predicted by supersymmetry, the leading extension to the Standard Model (see the article by Michael Dine in the Winter 1999 issue of the *Beam Line*, Vol. 29, No. 3). The lightest supersymmetric particle is thought to be stable. A neutralino with a mass just above the range excluded by current accelerator searches (mass > 32 GeV/c^2, depending on the theoretical model) could account for the non-baryonic component of the dark matter. However, it should be noted that no supersymmetric particle of any type has yet been observed, despite careful searches at accelerator laboratories. This somewhat tarnishes the luster of the neutralino as a dark matter candidate but doesn't deter the experimenters. It may be that current accelerators simply are too low energy, and a discovery awaits a future machine, such as CERN's Large Hadron Collider.

THOUGH WELL motivated, the above argument is basically theoretical conjecture. Modern cosmology has become an empirical science, and the next step is to seek observational or experimental evidence for such claims. A neutralino-type dark matter would be difficult, but not impossible, to detect. One approach is to search for it indirectly by looking for evidence of WIMP self-annihilation products, such as high-energy gamma's, antiprotons, or neutrinos. Various experiments are currently underway but have reported only negative results to date.

Another approach, taken by a number of groups, is to attempt the direct detection of these particles via their elastic scattering off an atomic nucleus in a crystal. These experiments are quite difficult: neutralino dark matter interacts in a detector extremely rarely—a few events per year per kilogram of detector mass. (Note that this implies that there is a WIMP collision with a nucleus in our bodies at very roughly a rate of one per day, but we certainly don't notice it!). Also, the very small energy deposition (only a few keV) is close to typical detection thresholds, so a very sensitive low-noise detector is required.

Distinguishing a positive signal from environmental backgrounds is another challenge for the direct detection of dark matter. In order to avoid being swamped by the usual low level radioactivity present in most materials, one needs to use the techniques of ultra-low-background experiments: the detectors and construction materials must be made of radio-pure materials, the experiment must be located deep underground to suppress cosmic-ray induced interactions, and the detectors must be carefully shielded.

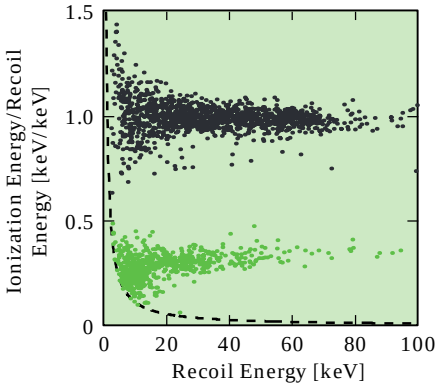
At present, there are about 20 WIMP direct detection experiments operating, employing a number of techniques. Scintillators (for example, sodium iodide) have been a favorite because a large mass is easily obtained, but these experiments

are hampered by the difficulty of performing active signal/background discrimination. Instead of performing an absolute rate measurement, these experiments look for a seasonal variation (annual modulation) in the WIMP rate. This is a predicted variation of a few percent as the velocity of the Earth around the Sun either adds to or subtracts from the Sun's velocity as we make our way through the galactic WIMP wind. Indeed, the Dark Matter (DAMA) experiment operating in the Gran Sasso underground laboratory in Italy has observed such a modulation over a four-year running period. If this were confirmed to be due to WIMPs, it would be the first evidence for the direct detection of dark matter.

AN ALTERNATIVE approach, pursued by our group, the Cryogenic Dark Matter Search Experiment (CDMS), has been the use of cryogenic detectors, a new kind of detector developed to conduct this experiment. CDMS, a collaboration of 10 university and national laboratory groups, has developed detectors which are able to measure the vibrations (phonons) of the crystal when struck by a single passing WIMP. By using germanium or silicon semiconductor crystals, we can combine this phonon measurement with detection of the ionization liberated by the recoiling nucleus. The advantage of this hybrid approach is that it provides a means of discriminating between a WIMP-generated nuclear recoil and a background-generated electron recoil. As shown in the illustration (upper right), nuclear recoils generate only about a third the ionization that an electron interaction of the same energy does. Hence, with this technique we can reject 99 percent of background events and our 250 g crystals are as sensitive as much more massive scintillator detectors. However, this technique does not let us reject events from background neutron interactions—these also produce nuclear recoils and so can mimic a WIMP signal. As described below, we have developed strategies to reduce and identify this neutron background, although this is what ultimately sets a limit on the sensitivity of this type of experiment.

In order to measure the recoil energy of the struck nucleus, it is necessary to cool the crystal to a temperature of 0.02–0.05 K to reduce thermal vibrations. We have developed two types of recoil energy sensors. Our first approach with detectors (developed in Bernard Sadoulet's group at the University of California, Berkeley) uses very sensitive thermistors bonded onto 165 g germanium crystals (photograph on right). These thermistors have a measurable change in resistance for the very small temperature rise in the crystal when it is struck by a passing WIMP.

A second approach (developed in Blas Cabrera's group at Stanford University) uses transition-edge sensors to measure directly the phonons generated in the crystal by the nuclear recoil. These sensors use a tungsten superconducting thin film deposited on a 250 g germanium (or 100 g silicon) crystal. The tungsten is maintained just below its superconducting transition temperature, and the energy liberated by the phonons causes enough of a temperature rise to produce a measurable increase in resistance.



As seen in these calibration data taken with test sources, cryogenic detectors can distinguish between background gamma rays (black points) which scatter off electrons in the crystal and neutrons (or WIMPs) which scatter off nuclei (green points).

S. Golwala

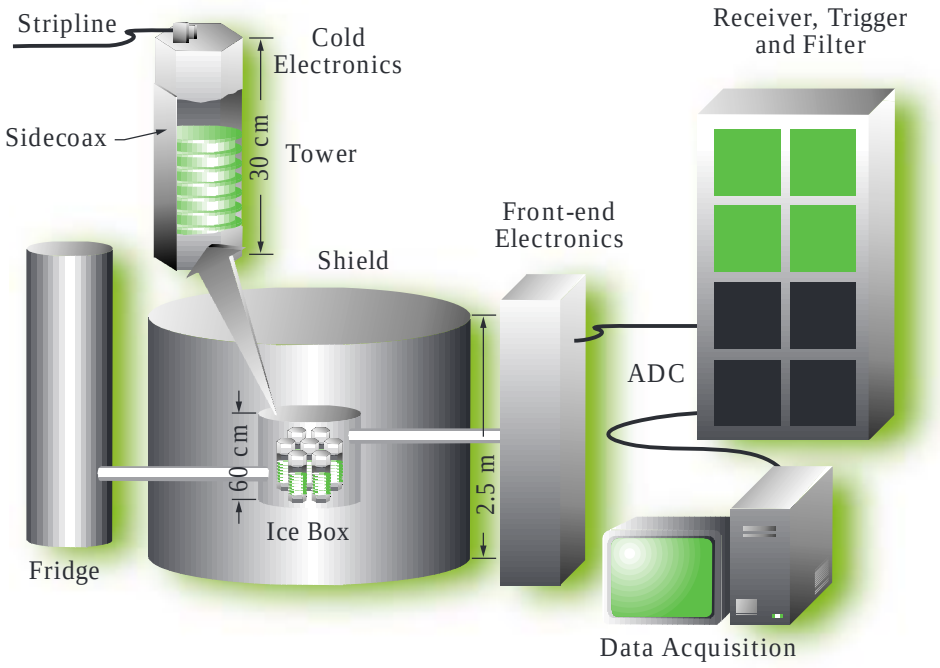
CDMS germanium detectors used in the 1999 run.

A simplified schematic of the experiment is shown below. In order to operate at such low cryogenic temperatures a ^3He–^4He dilution refrigerator is necessary. (This is not common equipment for a particle physics experiment, but it is the workhorse of low temperature physics laboratories.) In order to minimize any background radioactivity from the refrigerator construction materials, we have designed a unique cryostat ("ice box"), made of seven layers of nested copper cans, that provides a cold volume of about 1 cu ft separated from the refrigerator by about 10 feet. The cryostat is shielded by layers of lead and polyethylene. As is common in such low-background experiments, we use "archeological" lead for the innermost layer of the shield. In this lead, which can be obtained from ancient shipwrecks, the radioactive isotopes common in freshly smelted lead have decayed to low levels. Polyethylene is used to "thermalize" the neutrons. That is, by elastically scattering on the hydrogen nuclei in the polyethylene, the neutrons lose much of their energy and fall below our detection threshold. Finally, we cover the entire outside area with plastic scintillator to veto cosmic rays—or, more importantly, any backgrounds they generate such as neutrons.

To get started with the experiment, we have set up CDMS I, the first generation of the apparatus, in the former High Energy Physics Laboratory endstation on the Stanford University campus. This has been a very convenient location for our development phase, but as a low background facility, it is a relatively "shallow" site, having only 11 meters of rock overhead. Nevertheless, we have been able to use this facility to obtain physics results. A recently completed run, employing a set of three detectors for about a year, has made it currently among the most sensitive experiments searching for dark matter.

In our data we found 13 nuclear recoil events. Regrettably, they are probably not the WIMPs we've been hunting, but rather are best explained as simply neutron-induced background events. One strong piece of evidence that we are seeing neutrons is that we have four events with interactions in more than one crystal—this is predicted by our Monte Carlo for neutrons, but is extremely improbable for WIMPs. Another indication is from a run the previous year, using a silicon detector. Silicon is about as sensitive to neutrons as germanium, but is much less sensitive

The layout of the CDMS II experiment being installed in the Soudan mine.

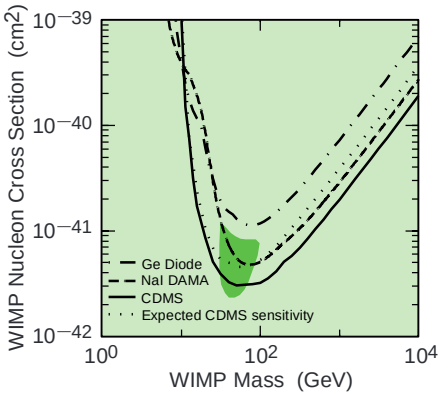


to WIMPs. We saw four events in the silicon run, consistent with the conclusion that we are seeing the background neutron flux of the laboratory. And, it is important to note that there is reasonable agreement between the Monte Carlo simulation of the neutron background and the observed rates. For these reasons, our data provide a null result. We exclude a region in the mass versus WIMP-nucleon cross-section parameter space (see the illustration on the right).

It should be noted that this null result is at odds with the WIMP interpretation of the DAMA annual modulation observation. The rate observed by CDMS would be consistent with DAMA if the 13 events were in fact WIMPs, but the weight of the evidence strongly favors the neutron interpretation. Both groups are planning to take more data. The DAMA group intends to double its detector mass, and we are planning a major upgrade of CDMS.

CDMS I has shown that cryogenic detectors can be used to perform a sensitive search for WIMP dark matter. But to make inroads on the question of whether neutralinos are the ubiquitous dark matter, we need a much deeper site in order to be shielded from cosmic rays. The collaboration has recently been funded by the Department of Energy and the National Science Foundation to build CDMS II, a new version of the experiment to be operated in the Soudan mine in northern Minnesota. (Note that this location, near the Canadian border, has the dubious distinction of often recording the coldest winter temperatures in the continental United States!) This former iron mine, now run as a state park, has been the home of the long-running Soudan II proton decay/neutrino detector. A new cavern is being excavated for the MINOS long baseline neutrino oscillation experiment from Fermilab (see the article by Maury Goodman in the Spring 1998 issue of the *Beam Line*, Vol. 28, No. 1). The laboratory area we will use for CDMS II is 700 meters underground, and at this depth the cosmic-ray muon rate is reduced by a factor of 10,000.

We are now embarking on the construction of CDMS II. For this experiment we will fabricate 42 new detectors, using transition-edge sensors. We will use both germanium and silicon crystals because, as we have found in CDMS I, their different relative responses to WIMPs and neutrons are a powerful technique for distinguishing a WIMP signal from the neutron background. We are building a new cryostat and shield and are installing a cleanroom in the underground laboratory. This construction will take about three years to complete. Even then, after it is fully assembled, we will need patience to operate the detectors for about three more years in order to obtain an exposure that will allow us to search for sypersymmetric dark matter with 100 times the current sensitivity. To rephrase an old adage, one might say the future is bright for doing cosmology deep underground.



The result from the CDMS 1999 run shown as an exclusion plot. The values of the WIMP-nucleon scattering cross section above the solid line are excluded (at 90 percent confidence level) by the data. The darker green heart-shaped region shows the allowed values from the DAMA experiment.

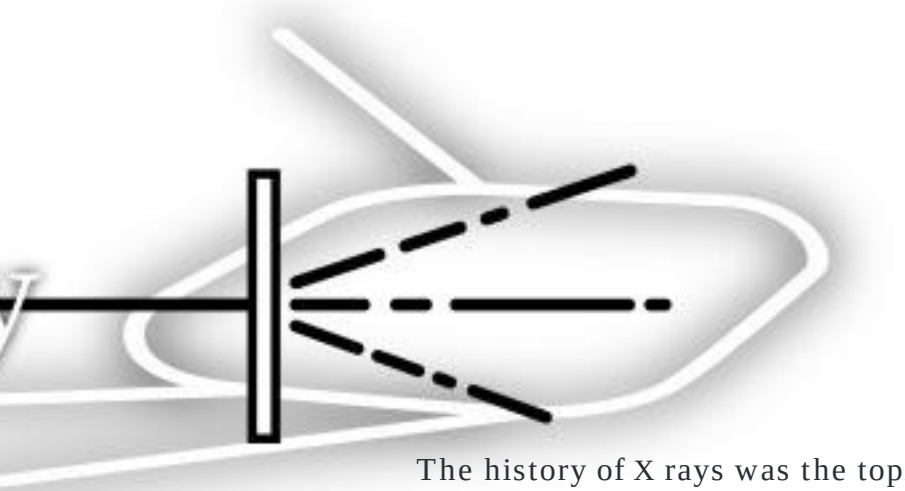
Proton Radiography

by EDWARD P. HARTOUNI & CHRISTOPHER L. MORRIS

BOOM! As beam arrives to your experiment the target is reduced to a twisted pile of rubble in an impressively energetic explosion, this after months of planning and hard work. Later inspection of the target reveals little information about how it got that way. Fortunately, your experiment is part of a plan to study the physics of explosions that push metal hard enough to make it flow hydrodynamically. Not only does this process happen on very short time scales, but much of what is interesting takes place deep within the moving metal itself. Further complexities arise when the exploding experiment is composed of many different materials, the behavior of each providing important clues as to what is happening in the system. This is a key problem faced by practitioners of the Department of Energy's Science Based Stockpile Stewardship, an ambitious program to allow our Nation to maintain its nuclear stockpile in a safe and reliable state and simultaneously support the Comprehensive Test Ban Treaty.

A solution to this experimental challenge lies in the use of radiography. Both Los Alamos and Lawrence Livermore National Laboratories have used X-ray radiography for many years to glean information about transient events occurring in exploding systems. To meet the goals of the Science Based Stockpile Stewardship program will require much more information about these systems. While X rays have many favorable attributes for radiography, using high energy protons as a radiographic probe has a number of exciting possibilities. Current accelerator technology could easily provide a source of protons for use in radiography.

Our work on proton radiography has applied ideas, measurements, and technology from nuclear and high energy physics. These applications were unanticipated when Los Alamos and Livermore initiated basic science programs in these fields. The laboratories had a vision that supporting basic science would provide a cadre of workers whose broad range of skills could be applied to programs of national



importance related to the mission of the laboratories. Proton radiography verifies this vision.

The application of proton radiography to a national need is another example of physicists applying their particular skills in the service of the Nation. It is important that physicists remain engaged at all levels of developing policy to insure sensible solutions are found to address important problems.

The history of X rays was the topic of the *Beam Line's* Summer 1995 issue (Vol. 25, No. 2). The realization that X rays could penetrate matter led almost immediately to the idea of a radiograph, an image produced by radiation other then visible light. The application of Wilhelm Konrad Roentgen's discovery to medical diagnostics gave doctors the ability to look within a living body. Over the last century, X-ray radiography has been applied to a number of applications in which the interior state of an object must be "viewed" without disturbing or destroying the object (non-destructive testing). X rays have also been used in investigating transient phenomena.

The method of making an X-ray radiograph is largely unchanged from Wilhelm Roentgen's technique (though the technologies for making and detecting X rays have changed greatly). A source of X rays is directed at an object, generally from a "point source." Behind the object is placed an X-ray detector (film, for example). The detector produces an image of the shadow cast by the differential absorption of the materials that compose the object.

The use of protons for medical radiography has been studied since 1954. Low energy protons (100–300 MeV) beams have been used at a number of locations throughout the world to treat various medical conditions. In conjunction with the treatments, the proton beams have also been used to radiograph the internal elements of the patients as part of the treatment planning. In these medical settings, the means of making a radiograph are similar to what was described above for X-ray radiography. The difference between X ray and proton differential absorption distinguishes the information contained in the radiographs.

PROTONS ARE FAMILIAR OBJECTS to nuclear and particle physicists. They comprise the charged component of nuclei and are (along with electrons) the fundamental objects of matter in the present day Universe.

For readers wishing to pursue issues in more detail related to the Science Based Stockpile Stewardship and the Comprehensive Test Ban Treaty programs, the following URLs may be helpful:

SBSS

http://www.dp.doe.gov/dp_web/public_f.htm

http://nepa.eh.doe.gov/eis/nometa/eis0236/toc.htm

CTBT

http://www.state.gov/www/ global/arms/ctbtpage/trty_pg.html

They have one unit of positive charge, plus they have a precisely known mass. They have one unit of "baryon number" and are the isospin partner to the neutron. They interact with other particles primarily through the electromagnetic and strong interactions. While physicists now regard the proton as composed of quarks and gluons, this level of detail is irrelevant to radiography.

The fact that protons and electrons are stable (do not undergo radioactive decay) and are readily available in ionic form (for example, ionized hydrogen, H^+) has allowed physicists to devise a number of ways to accelerate them to increasingly higher energies. Electrons were originally accelerated in cathode-ray tubes in experiments performed over a century ago. Protons have a more recent history in accelerators.

The strong interaction binds the nucleus together. The current theory of this interaction is Quantum Chromodynamics which, together with the Standard Model, explains much of particle physics. What is important to radiography is the phenomenological observation that the strong interaction has a very short range (roughly 1 fermi, equal to 10^{-15} meters). Since the proton and nuclei have dimensions of the same order (1 fermi) this means that the proton and other nuclei interact by hitting each other, something like billiard balls. The probability of collision is indicated by the quantity termed "cross section" and is measured in units of barns (a term taken from the quip "...couldn't hit the broad side of a..."). For proton-nuclei interactions, the cross section is approximately equal to the cross sectional area of the nucleus (given by the nuclear radius, r, as r^2, nuclei being, to very good approximation, spherical).

Another part of particle physics phenomenology is that the proton interaction cross sections are very nearly independent of the proton's energy at high energy (greater then 1 GeV). This fact makes interpreting proton radiographs easier because the probability of survival of the high energy proton is not affected by a change in its energy from other scattering processes.

Because the proton is charged, it interacts with matter through the electromagnetic interaction. As high energy protons traverse matter, they interact with the electric field of the nuclei, and with the atomic electrons orbiting those nuclei. The effects of these interactions are quite distinct. When the proton scatters off of the nucleus by way of the electromagnetic interaction, the effect is a small change in the proton's direction. These interactions are termed "elastic" scattering. Because the proton can scatter off of many nuclei as it makes its traverse, the effects of each of the small scatters can accumulate. This effect is called multiple Coulomb scattering because it is the result of many scatters off of the nuclear electric field which is described by the Coulomb potential. Because of many complications in this system (for example, the atomic electrons "screen" the nuclear potential from the protons) physicists use approximate formulas to describe the scattering involving bulk characteristics of the material to represent the probability of such a scattering process.

The consequence of multiple scattering for proton radiography is quite significant, especially for dense materials. That part of the beam which is not absorbed by the material is scattered by it. Straight-line rays no longer exist, and the shadow made by the object is blurred. In fact, the farther behind the object the detector is located, the more blurred the image. An innovative way around this multiple scattering was found to make it possible to separate the object from the detectors.

The proton interactions with the atomic electrons generally do not result in much change to the proton direction, but many scatters do reduce the proton energy. This is because the electrons might scatter so violently as to become unbound to the atomic nucleus. This process is known as ionization energy loss. With dense materials the energy loss can be quite large (100–500 MeV).

THE IDEA that protons could be used as a radiographic probe for thick dense objects to support the goals of the Science Based Stockpile Stewardship

program originated at Los Alamos National Laboratory (LANL) in 1995. The LANL physicists realized that the blurring of the object's shadow cast in the radiograph could be corrected by using a magnetic lens. Using magnets to focus beams of charged particles is common place at accelerator laboratories. The simplest magnets used for this purpose, called quadrupole magnets, have four poles alternating in sign. When used in combination, these magnets will bend charged particles of a particular momentum so that the rays which are multiply scattered going through the object will re-converge at a point downstream of the object to form an image. This was the innovative idea that opened the door to new applications for proton radiography.

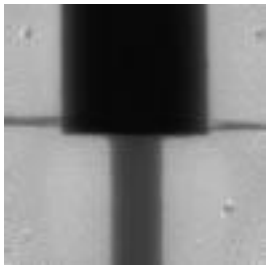
The LANL physicists quickly tested their ideas at the Los Alamos Neutron Science Center (LANSCE), a proton linear accelerator capable of producing a beam of 800 MeV protons. The beam can be pulsed and have a large number of protons, depending on the number of pulses produced. Their initial experiments led them in two directions. The first was to propose a more elaborate facility for proton radiography at LANSCE. The other direction was to test their ideas in a high energy beam of protons at Brookhaven National Laboratory's Alternating Gradiant Synchrotron (AGS) facility in New York.

The AGS experiment (E290), a collaboration of physicists from both LANL and Lawrence Livermore National Laboratory, was conducted in the A1 beam line in the summer of 1996. The beam line was rapidly converted to provide a magnetic lens consisting of four AGS beam line quadrupoles (8Q48's). The particles in this secondary beam had a 10 GeV/c momentum and consisted of 70 percent protons and 30 percent pions, the most common meson. The entire experiment took two weeks to set up and run. The images confirmed the physicists' expectations that their ideas would work at high energy.

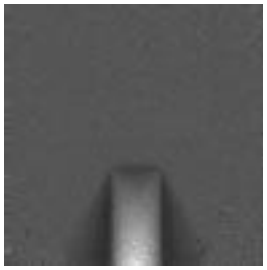
The E933 beam line at Brookhaven National Laboratory's Alternating Gradient Synchrotron. The view is looking downstream. The quadrupole magnets (octagon-shaped) are part of the first magnetic lens. The break in the beam pipe allows detectors to be set up at the first image station. Two camera systems are viewing the same scintillating fiber plane.

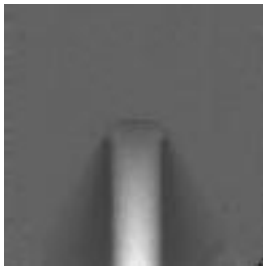
The ease with which this experiment was set up and run also points to the fact that proton radiography utilizes mature accelerator technology; existing accelerators and beam line technologies are adequate to meet the needs of proton radiography. E933, a follow up experiment to E920, is shown in the photograph above. It is located in the U-Line at the AGS.

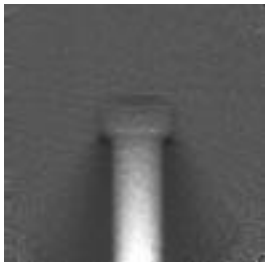
The detectors used for proton radiography can be designed to take advantage of the fact that protons are charged. This means that detectors used in nuclear and high energy physics experiments can be applied for radiography. In particular, these

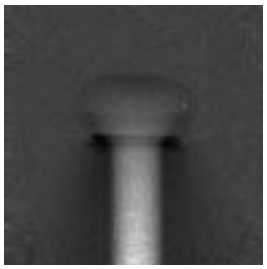


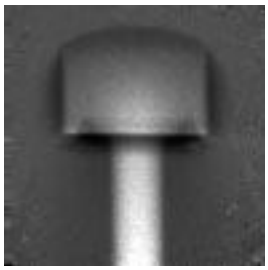
A time sequence from the Los Alamos LANSCE PRAD-50 experiment of a high explosive burn to determine how detonation waves propagate around geometric features. The first photo on the left shows two high explosive cylinders of different diameters before detonation. The high explosive is detonated from the bottom and the detonation wave propagates vertically. The figures are taken with different charged-coupled detector cameras at different times from 17.26 milliseconds to 23.70 milliseconds.











detectors will have high efficiency in detecting protons and at the same time have little effect on the proton beam. This enables multiple detectors to be placed in the radiography beam line to make multiple measurements of the radiographic image.

Some traditional radiography detectors have been used for proton radiography. These include imaging phosphor plates which act like photographic film (exposed when the protons penetrate the plate) and charged coupled device cameras that view a screen which scintillates when the protons pass through.

A new set of detectors is being designed and tested at Lawrence Livermore and Los Alamos national laboratories that allow multiple time frames of an image to be recorded. The frames have a duration of 50 nanoseconds (1 nanosecond is 10^{-9} seconds), a frame-to-frame spacing of 250 ns, and the ability to take tens or hundreds of frames.

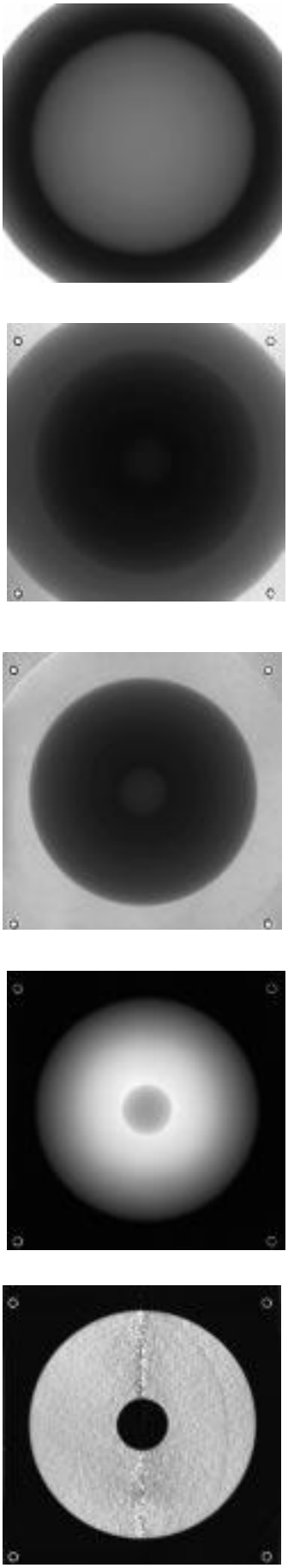
Making a movie to follow the internal dynamics of objects is one of the goals of applying proton radiography to the SBSS program. Along with detectors, accelerators must be capable of producing pulses of beams with a large number of protons in each pulse. Protons circulating in synchrotrons have a pulsed structure because of the fact that the radiofrequency (rf) accelerating cavities must have a well defined frequency in order to accelerate the beam. As the protons circle around the accelerator, they arrive at the rf cavity at some well-defined time depending on their velocity. The rf cavity is setup to give the protons a little acceleration "kick." As the protons move faster, the rf frequency and phase is adjusted to give the kick at just the right time. Because the rf is sinusoidal in the cavity, the kick can occur at each period of the rf, which means that if the period is short compared to the orbit time of the proton beams, many proton beam bunches can be accelerated simultaneously.

Once the protons achieve their maximum energy, the beam bunches can be extracted from the synchrotron by way of a well practiced set of beam gymnastics. These pulses fall on the changing object at different times and are detected at various image points in the radiography beam line, one image for each pulse. In this way a radiographic movie is made with the pulses of protons from the accelerator. The photographs on the left show the time sequence radiographs from a LANSCE experiment investigating the behavior of a high explosive burn.

The changing shapes of the object are only part of the information proton radiography can provide. Both the density of the material in the object and the identity of that material may be obtained. To make these measurements we require some information about the nuclear scattering length and the radiation length of the material. We obtain this information by making radiographs of objects varying in thickness made of known materials with known densities. We can predict what the radiograph will look like and adjust the scattering and radiation lengths to make the prediction agree with the radiograph. This procedure takes into account a particular radiography beam line setup.

The density of the radiographic object can then be found given the

Steps in reconstructing the volume density of the French Test Object from the Brookhaven National Laboratory E933 data. A model of the overlaying, partially seen material (mostly foam and copper) is formed into a "synthetic radiograph" in the top right image. This is ratioed with the actual data (second image), for which the beam and the detector artifacts have been removed, resulting in the third image. The logarithm of the ratio image is then normalized by the scattering length to give the "areal" density (fourth image). Finally a mathematical procedure uses the fact that the object has cylindrical symmetry to reconstruct the volume density of the French Test Object. A slice through the reconstruction is shown in the bottom image.



beam path length through different parts of the object and the scattering constants. Finding the path lengths involves making a three-dimensional reconstruction of the object. This procedure, known as tomography, may use many different views of the object taken simultaneously, or some known property of the object's shape (for example, the object might be spherical). The measured intensity of the object depends on the product of the density and the path and the scattering lengths. Knowing the path length and the scattering length, the density is then recovered. The images on the right show the steps reconstructing the French Test Object, a series of nested spherical shells made of plastic foam, copper, tungsten, and air.

Identifying the material is somewhat more difficult and involves two different but simultaneous measurements. The multiple scattering depends on the radiation length of the material. A material with a large radiation length scatters the beam less then a material with a short radiation length. The material identification is the result of comparing a radiograph which sees different amounts of the multiple scattering angles. This can be arranged by putting two magnetic lenses, one after the other, in the beam line. The first lens sees all multiply scattered protons from the object and records them at the lens' image location. The protons pass unaffected through the first detector and into the second lens. The second lens contains a collimator that absorbs protons with large scattering angles (collimators can be made to absorb only small angle scattered protons too). The second lens images the protons at the second detector. When these two images are compared, the relative amount of intensity of the images is used to extract the ratio of the path length-to-radiation length. Knowing the path lengths of the protons through the object allows the radiation lengths to be determined. The radiation lengths then provide the information about materials.

THE WORK of the last five years by physicists from Los Alamos and Lawrence Livermore national laboratories has helped to develop proton radiography to the point where the important Science Based Stockpile Stewardship facility, the Advanced Hydrotest Facility, is considered to be devoted to proton radiography. It will be capable of investigating the behavior of the Nation's nuclear stockpile safety and reliability. This facility is in the conceptual stages of development and will be located at the Los Alamos site. Physicists from both laboratories will perform many tests and experiments in support of their Science Based Stockpile Stewardship activities.

This facility will also provide a research and development base for the industrial applications of proton radiography. Some of these applications might include the investigation of combustion in automobile engines and various non-destructive testing procedures, such as material identification.

Astrophysics Faces the Millennium II

The Stained and Spotty Heavens

by VIRGINIA TRIMBLE

Fabricius finds certain spots and clouds in the sun.

—Robert Burton (1577–1640)
Anatomy of Melancholy, Part II, Sect. 2.

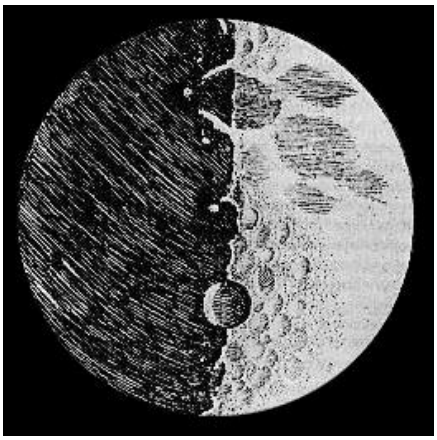
"Immaculate" is, most literally, "unstained," with a variety of extended meanings in the directions of perfection, exact circular or spherical shape, freedom from sin, and really unlike my kitchen floor. Though terrestrial objects could be any old shape or mix of colors, heavenly ones were supposed to be immaculate in the medieval synthesis associated with the name of Thomas Aquinas (1225–74). The idea sounds a bit less strange if you keep in mind that farther from Earth meant nearer to G.d, who was, by definition, perfect.

The concept was necessarily from the beginning a bit fuzzy at the edges. The only way to miss seeing light and dark areas on the moon is to avoid ever looking at it except in its thinnest crescent phase—early to bed, early to rise, and all that, though myopia at the -9 diopter level or more also works. Well, OK. The moon was just at the edge of the terrestrial/celestial divide, accounting for its stains. But the presence of mountains, capable of casting shadows, was an unwelcome surprise to many who heard or read Galileo's 1610 announcement. Incidentally, his drawings were actually pretty good, and the shadow patterns in the earliest versions can be associated with particular lunar features, though later reproductions tended to degrade to something like "chicken pox of the limb." Sporadic handles or appendages on Saturn were similarly worrisome that same year, and not until the winter of 1655–56 did Christian Huygens recognize the phenomena as being due to a thin, tilted ring, which we see in

different orientations through the planet's 30-year orbit period. Apparently those long Dutch winters can be used in many ways.

But it seems to have been dark spots on the supposedly immaculate Sun that caused the most distress. Wait a minute, you will be saying. Surely there are naked-eye sunspots. There are indeed, at least on hazy, dusty, or foggy days, when the Sun is fairly close to the horizon. Chinese and Korean astronomers had recorded something like 150 examples between 165 BC and about 1400 AD (when perhaps Western ideas of what you were supposed to see on the Sun began reaching them). No Far Eastern drawings of sunspots from this period have been found so far, but spots are described as like swallows, magpies, and various other birds. Since they were known to last for days, one cannot suppose there was any confusion with silhouettes of actual birds, but only a search for descriptions that could be interpreted as favorable to the astronomer's current or prospective boss.

Arab and European astronomers very occasionally noted sunspots between 800 and 1400. Climatic conditions, lack of interest, and sunspot cycles of various lengths can be invoked to explain the rarity of Western reports. (It has also been widely claimed that Europe was very cloudy the year the supernova of 1054 was visible from China.) But only a definite mind-set on the part of the reporters can account for all the Arab and many of the European sightings being attributed to transits of Mercury and Venus. Transits of Mercury are never naked-eye events, for its disk is only 12 arcseconds across. Those of Venus are exceedingly rare, and modern computations show that none of the spot reports came from days of real transits. In addition (and this would have been



A reproduction of a reproduction of a reproduction of one of Galileo's early drawings of the moon. It shows the sunrise limb, with shading that makes clear that the circular features have raised, mountain-like edges and lower centers. Galileo also described the lunar maria ("seas"), thinking they were filled with water, as did many later generations of astronomers.

Sunspot drawing in the Chronicles *of John of Worcester, from 8 December AD 1128. Notice the depiction of the penumbra around each spot. (Courtesy Corpus Christi College, Oxford, Ms 157, p. 380)*

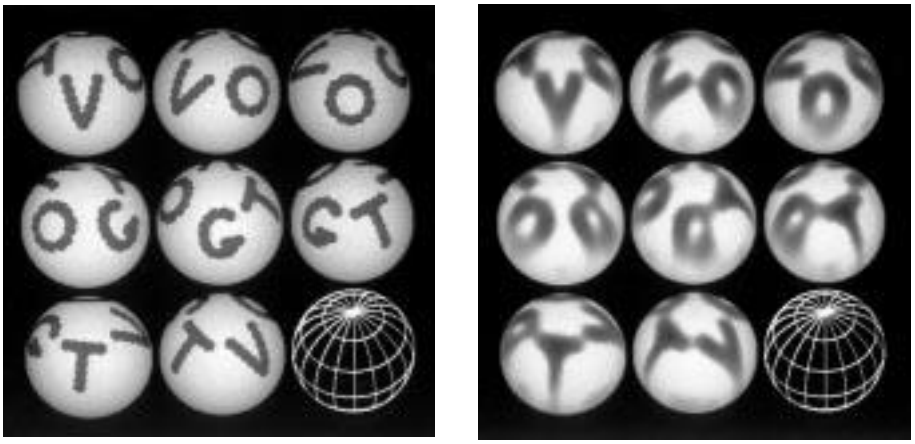
obvious to any rocket scientist of the year 831 who thought about the issue), such transits can last only a few hours, while sunspots sometimes remained visible for a week or more. The observers simply did not want to see, or admit to having seen, spots on the Sun. The one pre-telescopic drawing, from England in 1128, carries a caption that, in recent translation, speaks of "two black spheres against the Sun," that is, once again, intervening bodies of some sort.

Galileo proclaimed that the spots were intrinsic to the Sun, changing apparent positions because of solar rotation. And that I mention him first is an example of the common injustice called the Matthew effect. Thomas Harriot in England had turned telescope upon the spots earlier than Galileo, and Johann Fabricius of Frisia (look it up; you have a Gazateer!) had proclaimed them to be surface phenomena, tracing the solar rotation, first as well. Indeed the contrary, "satellites of the Sun," hypothesis was also already in print, from Scheiner, a German Jesuit, before Galileo's *Letters on Sunspots* reached paper. None the less, when *Physics World* asked its readers to vote for the most important physicists of the last thousand years, Galileo got a lot more votes than Harriot and Fabricius. Admittedly, he was first past the post on a great many other issues.

Perfect circles had already suffered one blow that decade, when Kepler's *New Astronomy* (1609) declared that the orbits of the planets must be ellipses (with the Sun at one focus; $P^2 = a^3$; and the equal areas law) in order to match planetary positions in the sky at the accuracy recorded by Tycho Brahe. Kepler nevertheless attempted to preserve one part of the heavens for geometry, by deriving the spacings of the planets (that is the *a* values) from a nesting of the platonic solids. The algebraic version is the 18th century Bode's law, not, of course, a law or first thought of by Bode or Titius. And the 1999.99 explanation of the spacing of the planetary orbits involves both tidal interactions and some chaos, in which Jupiter, Saturn, Uranus, and Neptune may all have formed about the same distance from the Sun and kicked each other around and out. The computations are close relatives of those being used to account for "hot Jupiters," massive planets orbiting other stars in short-period orbits.

OTHER SPOTS

Well, that is what became of Kepler's platonic solids. What about various kinds of spottiness and acircularity over the years? The Great Red Spot on Jupiter was discovered in 1644, and had not necessarily been there forever, waiting patiently. Its size, color, and location all vary, and smaller spots on both Jupiter and the other Jovian planets definitely come and go. A completely fictitious tale records what might have happened in 1688 or thereabouts, if Newton had tried to describe his universal gravitation before a modern-style meeting of the Royal Astronomical Society (not founded until the 1820s). The end point is an elderly fellow garumphing, "Well, young man, and can this wonderful new theory of yours explain the Great Red Spot on Jupiter, one of the most puzzling phenomena of the solar system?" The answer, of course, is no. And we can claim at least enough understanding today to recognize that A. Fellow was asking a silly question. The Red Spot was a Taylor column when I was a girl. It is now, very crudely, part of the Jovian weather pattern, and so rather different from sunspots, which are regions of concentrated solar magnetic field.



A computer-generated rotating, spotted star and its reconstruction from simulated spectroscopic data (shapes of absorption lines produced in the cooler gas of the dark regions). The coordinate grid at lower right shows the location of the rotation pole. The time sequence of snap-shots in both the original "star" and its reconstruction runs left to right across top, middle, and bottom of each drawing as the star rotates clockwise as seen from above. (Courtesy Steven S. Vogt, UCO/Lick Observatory)

Once both the spottiness and the starriness of the Sun were part of the astronomical armamentarium, star spots were a natural extrapolation. The 17th century French priest-astronomer, Ismael Boulliau, proposed that variable stars, of which some dozens were by then known, were spotted like the Sun, but much more extensively, so that their apparent brightnesses could vary by factors up to ten or more through their rotation periods. Boulliau is sometimes held up as a Horrible Example of the perils of unjustifiable extrapolation. And indeed most variable stars are pulsating singletons, eclipsing pairs, or unsteady accretors of gas from their surroundings.

But other stars are spotted, they do rotate, and a careful watcher can see the periodic brightness variations, though they are generally at most a percent or so of the total brightness. The record (185 percent) is held by a very young and otherwise fairly peculiar star. In fact you can do better than just see the amount and period of the brightness variations. By concentrating on the shapes of the absorption lines that are strongest in cool gas, you can locate particular spots in latitude on the star, watch them move across in longitude through the rotation period, and follow fading old and growing new spot complexes. The idea, now called Doppler tomography, goes back to a 1958 symposium presentation by Armin Deutsch of Mt. Wilson Observatory.

Much of the recent implementation has been the work of Steven Vogt of Lick Observatory, who, in a triumphant vindication of the method, was able to recover an artificial spot distribution put on a virtual star and turned into Doppler line data by a challenger. The spot pattern spelled out VOGT across the star. You can see why this was not done by an astronomer named Fritze-von Alvensleben. Actually there is another reason. She works on extra-galactic topics.

Analysis of star spots in this way provides much of our knowledge of stellar rotation rates and levels of activity as a function of star mass, surface temperature, and age. The data are complimentary to those coming from X-ray and radio observations and from monitoring emission lines of stellar chromospheres and coronae. Direct Zeeman measurements of magnetic field strengths in ordinary star spots is only just becoming possible. Many are in the 100s–1000s of Gauss range characteristic of the Sun. And, if you want to be really spotty, it is important to be young, rapidly rotating, and possessed of a deep convection zone. Eating chocolate probably doesn't matter.

The spottiest, fastest-rotating, most active stars tend to have polar spots rather than equatorial or mid-latitude solar-style ones. Activity cycles, like the 11-year solar one, are fairly common. Periods range from 5 to at least 20 years (perhaps an observational limit). The most-active stars with the most spots vary in coverage and emission line strength, but are not obviously cyclic.

POLAR SPOTS

Have we exhausted the possibilities of star spots in modern astronomy? By no means. White dwarfs and, especially, neutron stars with strong magnetic fields have extremely uneven surface emissivity,* generally brightest at the magnetic poles. The magnetic poles are oblique to the rotation ones, and gas can stream in or out along the field lines. One category of stars with polar magnetic spots you have been hearing about for 30+ years. They are the pulsars. Some classes of binary, variable X-ray sources also feature spotty neutron stars. The spots can be hot or cool as well as high or low in magnetic flux. Similar, though less spectacular, variability characterizes magnetic white dwarfs accreting from fluffier companions. The classes are called DQ Her stars, intermediate polars, and other names of at most moderate informativeness.

Let us pay one last visit to the solar system to look at some bodies that can be both spotty and non-spherical. I mean the smaller moons, asteroids, and comet nuclei. They too vary in brightness as they rotate, and we can separate the effects of shape and of reflectivity only for those whose images are resolved. Saturn's moon Hyperion, on the one hand, comes close to being black on one side and white on the other, while Mars' Phobos and Demos are shaped like primitive stone tools whose flint-knapper gave up in the middle of the task. Physically possible rotation periods range from a few minutes to many years. Most are of order a day.

SPHEROIDS, ELLIPSOIDS, AND HIGHER-ORDER ASYMMETRIES

Most astronomical objects large enough for gravity to beat electromagnetism are, in fact, rather spherical. This includes moons, planets, stars, large star clusters, galaxies (at least the dominant gravitating mass), and the larger clusters of galaxies. The most pervasive and conspicuous deviations arise from rotation, and it is customary to begin by invoking the names of Maclaurin and Jacobi and equilibrium figures of rotation for spheroids and triaxial ellipsoids. (Yes, you may have a moment off to go look up which is which and to get a cup of coffee while you're at it). Modern calculations include effects of pressure, general relativity, and whatever else may be necessary. The usual starting point is a book by Chandrasekhar, and, occasionally, one by R. A. Lyttleton. Herewith a few interesting cases.

For stars, the amount of rotational distortion can be thought of as probing either their density as a function of radius or whether the internal angular velocity is the same as that of the surface. "No major surprises," is a reasonable summary. But readers in late youth may recall that Robert Dicke, in the 1960s, suggested our Sun might have a rapidly rotating interior. This would produce a large second (quadrupole) moment of inertia, J_2, which, in turn, would be responsible for some of the measured advance of the perihelion of Mercury, leaving less to be accounted for by non-Newtonian gravity. Dicke also had a theory of gravity, with both scalar and tensor potentials, that just nicely produced somewhat less perihelion advance than you expect from general relativity. His goal was to make gravity in some sense "more Machian," so that local processes reflect the properties of the whole universe. I have no opinion on whether Brans-Dicke or any other scalar-tensor theory succeeds with this mission. It is perhaps worth noting that non-GR theories come along every few years, and recent proponents of them have simply sat back and waited for someone else to do the work of testing them.

Dicke, however, set out to measure the shape of the surface of the Sun as precisely as possible. And, indeed, he found the equatorial diameter to be larger than the polar diameter by just about the amount (parts in 10^5) needed to make all the beans come out even. He was, it now seems clear, doing solar surface physics by a very difficult method. The initial observations were made near the peak of a solar cycle, when facular areas near

Apologies for the pompous phrase. It is near the end of the semester, and I feel a sudden desire to take advantage of speaking to adults with considerable knowledge of science beyond what I have been able to tuck into students' reluctant craws over the past 14 weeks.

Robert H. Dicke, inventor of the Dicke (switching) radiometer, the Brans-Dicke theory of gravity, and much else. In 1965 he and his group were in the process of instrumenting a radio antenna to look for radiation left from the Big Bang when Arno Penzias and Robert W. Wilson found it while studying the microwave sky for communication purposes. He received the Tinsley Prize of the American Astronomical Society shortly before his death and deserved many more. (Courtesy AIP Emilio Segrè Visual Archives)

the equator make those regions brighter than high latitudes, and Dicke's method was sensitive to extra brightness, as well as extra area, near the equator.

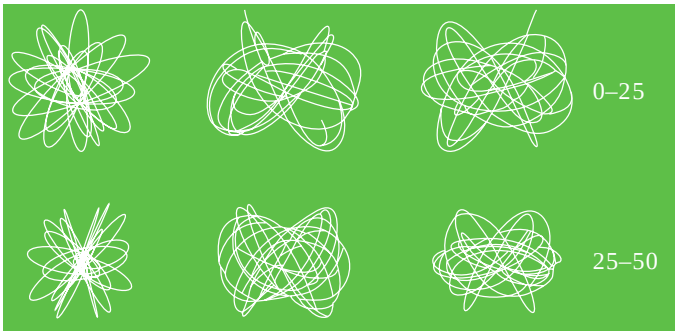
The modern calculated value for J_2 is 1.6×10^{-7}, and the observational upper limit, from lunar libration, is 3×10^{-6}, about an order of magnitude smaller than what Dicke had in mind. Analysis of solar normal modes (helioseismology) now says independently that the interior is not rotating significantly faster than the surface.

Galaxies, in contrast, have provided some surprises. You already know that the bright part of a spiral galaxy like ours is a rotating disk, usually somewhat flatter than a pancake, but not quite as flat as a tortilla. Less obvious is that spirals also have old stars and globular star clusters whose distribution is much more nearly spherical, and which do not share the rotation of the disk. But you probably know, too, that most of the mass in these galaxies is not in either the disk or the visible halo. It is the notorious dark matter, and determining the shape, let alone the rotation speed, of something you cannot see is a bit of a challenge. Indirect information comes from the orbits of the halo stars and clusters and from the flaring of the thin disk far from galactic centers. The best fit shape is an oblate spheroid. Axial ratios from 0.9 down to as small as 0.3 have been claimed. The short axis is (obviously?) perpendicular to the disk. Dark halos may even be somewhat triaxial.

Elliptical galaxies were long assumed to approximate maclaurin spheroids. They certainly look it, at first examination. A confirmatory measurement of the rotation speeds of the more squashed-looking ones was not, however, easy to come by. Spirals have emission lines from both ionized and neutral gas in their disks, relatively easy to record on a photographic plate or with a radio telescope. Ellipticals do not. All you have to go on is the sum of the absorption lines from the spectra of their constituent stars. I actually asked to be allowed to try to measure elliptical rotation curves as my Ph.D. dissertation and was told no. And a good thing it was; I would have found no rotation, and nobody would have believed that this was the right answer.

The first persuasive data came a decade after (1977) from Garth Illingworth (his dissertation, it turns out). Ellipticals, even highly flattened ones, generally don't rotate, he found. And so it remains. Modeling what they actually do has become an important topic in galactic dynamics, and the last subject to which Martin Schwarzschild made a major contribution. On the observational side, the deconvolution of many two-dimensional distributions of brightness on the sky into possible three-dimensional distributions of luminosity in space has gradually led to the official word being "triaxial."

The problem for theorists is then to figure out a gravitational potential shape within which visible stars can move to produce the observed luminosity distribution and the line widths (velocity distributions) along various sight lines through the galaxy that we measure. Schwarzschild's contribution was to insist that, when you had finished, the sum of the gravitational



Tube orbit switching to box orbit. Notice that the names describe the volume filled after a long time, and that the odd shapes arise because the orbits (unlike ones around a single point mass) do not precisely repeat. (Courtesy Tjeerd S. van Albada)

potentials of the stars in their orbits must add up to the one you had started with. This is unquestionably the right thing to do if the galaxies are made up entirely of stars. If most of the gravitation is due to dark matter, it may not be. In either case, the possible orbits are much more varied that mere conic sections. Some are banana-shaped (and avoid the center of the potential); others fill up boxes with curves that look like lissajous figures. Peanuts are also possible. The task of making the stars add up to the light and line profiles that you see, while remaining consistent with the potential you have chosen, is an on-going one.

AUX ARMES

Finally, no discussion of astrophysical asymmetries can be abandoned without mentioning spiral arms. They are ubiquitous in spiral galaxies (duh), and at least moderately frequent in other rotating gaseous disks, including those around stars in the process of formation and those around white dwarfs that are accreting gas from companion stars. Configurations with one, two, three, or four arms all happen. Twosies are the prettiest as well as the most common and are generally regarded as the norm. Physically arms are of (at least) two types. Some (called "grand design" in galaxies) are solitons, long lived, and mathematically interesting. Others (called "flocculent" in galaxies) are transient and the analog of the single drop of cream dripped into rapidly rotating coffee in a cup. This works, by the way. I saw it for the first time this fall, with thanks to Mr. Merrick Berg of Astro 498N. Sometimes you can even see the wave reflect back off the side of the cup.

In galaxies, the role of the cup is played by the outer Lindblad resonance. There is also an inner Lindblad resonance (which is sometimes where bars in barred spirals end) and even two Lindblads, though both resonances are named for the elder, Bertil. They are resonances among sums and differences of three frequencies, that of rotation of the gas, that of rotation of the spiral pattern, and the epicyclic frequency at which a test particle in the disk will oscillate around its equilibrium position in the rotating coordinate system.

And, having listened to this much dynamics, you are entitled to another cup of coffee in which to try the drip-of-cream experiment. I would suggest red wine, but am not sure it is improved by cream. Oh well, yes, I have tasted wine that would be improved by a drop of gall and wormwood.

SOURCES AND ADDITIONAL WISDOM

M. A. Hoskin (Ed.) 1999, The Cambridge Concise History of Astronomy remains immanently plagiarizable.

K. R. Lang, 1999, Astrophysical Formulae, 3rd Edition, now in two volumes, from Springer, is an excellent place to check on things like Lindblad resonances, Jacobi ellipsoids, and a usable expression for synchrotron radiation.

R. A. Lyttleton, 1953, Theory of Rotating Fluid Masses was published by Cambridge University Press, and

S. Chandrasekhar, 1969, Ellipsoidal Figures of Equilibrium by Yale University Press.

The first Sunspot drawing is described by I. R. Stephenson and D. M. Willy in Astronomy and Geophysics (a publication of the Royal Astronomical Society) Vol. 40 (though it is only two years old), 6. 21.

The completely apochryphal Newton story was told by the late Raymond Arthur Lyttleton.

CONTRIBUTORS

KIM GRIEST is a leader in the field of dark matter, especially in the search for its identity. This mysterious material fills galactic halos and is by far the most common material in the Universe. Trained in cosmology and particle physics, Griest's current research involves the theory and experiment of testing two of the most likely dark matter hypotheses. In the first he uses the gravitational lens effect to search for what he has dubbed MACHOs, including black holes, brown dwarf stars, or jupiter-like objects, which do not shine brightly enough to be seen in telescopes. The second involves the search for WIMPs, which, if they do exist, may be the dominant substance of the Universe.

He received his Ph.D. at the University of California, Santa Cruz, in 1987 and performed research at the University of Chicago and UC Berkeley, before joining the faculty at UC, San Diego. Griest is currently professor and vice-chairman of the UCSD Physics Department.

ANTHONY SPADAFORA is the Associate Director of the Center for Particle Astrophysics at UC Berkeley. He received his Ph.D. from the University of Illinois, working on the Mark III experiment at SLAC. After a two-year postdoctoral position at the Laboratoire de l'Accélérateur Linéaire in Orsay, France, he began working at Lawrence Berkeley National Laboratory on the DØ experiment at the Fermilab Tevatron Collider. In 1995, he joined the Center for Particle Astrophysics (CfPA), shifting his research from accelerator-based experiments to particle astrophysics. At the CfPA, he divides his time between Center administration and project management for the Cryogenic Dark Matter Search Experiment.

CHRISTOPHER L. MORRIS received his B.S. in physics from Lehigh University in 1969 and a Ph.D. in physics from the University of Virginia in 1973. He became a staff member at Los Alamos National Laboratory in 1976, and was made a fellow in 1996. In addition, he is a fellow of the American Physical Society. His primary field of research is nuclear physics. He has done much work in the field of medium energy nuclear physics and more recently has been developing a source of ultracold neutrons to be used for neutron beta decay measurements. He is the author of over 250 articles in refereed journals.

ED HARTOUNI has spent his career working as an experimental high energy physicist. His first research experience occurred as an undergraduate working with Gerson Goldhaber at UC Berkeley to analyze the SLAC SPEAR data which led to the discovery of the *J/psi*. For his Ph.D. thesis at Columbia University, he worked on Wonyong Lee's photoproduction experiment at Fermilab.

A change-of-career decision brought him to Lawrence Livermore National Laboratory with the idea of doing more applied research—little did he think this would be in applied high energy physics. In addition to this work, he is active in the MINOS collaboration at Fermilab and in the PHENIX collaboration at Brookhaven National Laboratory's RHIC.

VIRGINIA TRIMBLE has advanced (?) from chair-elect to chair of the Division of Astrophysics of the American Physical Society at its April 2000 meeting. This means that she bears a significant fraction of the blame for the sessions at the April meeting sponsored or co-sponsored by DAP. The complaint line forms just behind the lines to complain about other things she had done in recent years as a member of various boards and committees for the American Astronomical Society, the International Astronomical Union, etc., and will be followed immediately by the line of complaints concerning her actions as the astrophysics adjectival editor of *Reviews of Modern Physics* (2000–2002).

DATES TO REMEMBER

Jul 3–6	Advanced School on Quantum Chromodynamics (QCD 2000), Benasque, Huesca, Spain (S. Perris, Fisica Teorica & IFAE, Universitat Autonoma de Barcelona, E-08193 Bellaterra, Spain or qcd2k@ifae.es)
Jul 3–7	7th Inter-American Conference on Physics Education, Porto Alegre, Canela, Brazil (http://www.physics.umd.edu/robot)
Jul 4–6	5th IEEE Symposium on Computers and Communications (ISCC 2000), Antibes, France (http://www.rennes.enst-bretagne.fr/~afifi/iscc/2000.html)
Jul 10–15	Strings 2000, Ann Arbor, Michigan (Tina Wells, Randall Laboratory, University of Michigan, Ann Arbor, MI 48109-1120 or strings2000@umich.edu, http://feynman.physics.lsa.umich.edu/strings2000/)
Jul 10–16	3rd International Conference on Dark Matter in Astro and Particle Physics (Dark 2000), Heidelberg, Germany (H. V. Klapdor-Kleingrothaus, Max-Planck-Institut f. Kernphysik, Postfach 10 39 80, D-69029 Heidelberg, Germany or dark2000@mpi-hd.mpg.de)
Jul 10–23	Research Workshop on Calculations for Modern and Future Colliders, Dubna, Russia (mikhs@thsun1.jinr.ru or http://thsun1.jinr.ru/meetings/2000/)
Jul 12–15	Cosmology 2000, Lisbon, Portugal (Maria Bento, Departamento de Fisica, Instituto Superior Technio, Lisbon 1049-001, Portugal or bento@sirius.ist.utl.pt)
Jul 13–14	1st International Workshop on Mechanical Engineering Design of Synchrotron Radiation Equipment and Instrumentation (MEDSI 2000), Villigen, Switzerland (M. Bugmann, PSI, 5232 Villigen PSI, Switzerland or marien.bugmann@psi.ch or http://www.psi.ch/sls)
Jul 17–28	Conference on Cosmology and Particle Physics (CAPP 2000), Verbier, Switzerland (Kerstin Kunze, Universite de Geneve, Departement de Physique Theorique, 24 Quai E. Ansermet, 1211 Geneva, Switzerland or capp2000@nxth04.cern.ch or http://wwwth.cern.ch/capp2000/cap2000.html)
Jul 20–25	5th International Conference on Strangeness in Quark Matter (Quark Matter 2000), Berkeley, California (Grazyna Odyniec, Lawrence Berkeley National Laboratory, MS 70-319, 1 Cyclotron Rd., Berkeley, CA 94720 or G_Odyniec@lbl.gov or http://www-rnc.lbl.gov/S2000/)
Jul 27–Aug 2	30th International Conference on High-Energy Physics (ICHEP 2000), Osaka, Japan (Yori Nagashima, ichep2000@hep.sci.osaka-u.ac.jp)
Jul 31–Aug 5	Summer School on Theoretical Physics, Zacatecas, Mexico (V. V. Dvoeglazov, Escuela de Fisica, Universidad Autonoma de Zacatecas, Apartado Postal C-580, Zacatecas 98068 Zac, Mexico or valeri@ahobon.reduaz.mx)

Aug 3–5	Workshop on Low-Energy pbar Storage Ring (Pbar2000), pbar 2000 Workshop Secretariat, Physics Division, Illinois Institute of Technology, 3101 S. Dearborn St., Chicago, IL 60616 or pbar2000@hep2.phys.iit.edu)
Aug 9–12	DPF 2000, Meeting of the Division of Particles and Fields of The American Physical Society, Columbus, Ohio (dpfinfo@dpf2000.org)
Aug 14–16	Workshop on Applications of Synchrotron Light to Magnetic Materials, Campinas, Brazil (Lab. Nacional de Luz Sincrotron, LNLS, CP 6192, CEP 13083-970, Campinas SP, Brazil or secre@lnls.br)
Aug 14–25	28th SLAC Summer Institute on Particle Physics: Neutrinos from the Lab, the Sun, and the Cosmos (SSI 2000), Stanford, California (Ellie Lwin, Conference Coordinator, SLAC, MS 81, Box 4349, Stanford, CA 94309 or ssi@slac.stanford.edu)
Aug 20–Sep 2	European School of High-Energy Physics, Caramulo, Portugal (Claire Earnshaw, School of Physics, CERN/DSU, 1211 Geneva 23, Switzerland or Claire.Earnshaw@cern.ch)
Aug 21–25	20th International Linac Conference (Linac 2000), Monterey, California (Maura Chatwell, SLAC, MS 26, Box 4349, Stanford, CA 94309 or linac2000@slac.stanford.edu)
Aug 21–25	7th International Conference on Synchrotron Radiation Instrumentation (SRI 2000), Berlin, Germany (kongresse@wtb.tu-berlin.de)
Aug 26–31	Photon 2000: International Workshop on Structure and Interactions of the Photon (including 13th International Workshop on Photon-Photon Collisions), Ambleside, Lake District, England (photon2000@hep.lancaster.ac.uk)
Sep 4–8	4th International Conference on Particle Physics (COSMO 2000), Cheju Island, Korea (cosmo2K@alpha.kias.re.kr)
Sep 6–10	International Conference on Physics for the 21st Century, Rome, Italy (Liu Catena, Physics Department, University of Rome 'Tor Vergata,' Via dell aRicerca Scientifica 1, 1-00133 Rome, Italy or catena@roma2.infn.it)
Sep 10–15	18th Advanced ICFA Beam Dynamics Workshop on the Physics Of and the Science with X-ray Free Electron Lasers, Arcidosso, Italy (Linda Lareneta, larenta@physics.ucla.edu)
Sep 13–18	Beauty 2000: 7th International Conference on *B* Physics at Hadron Machines, Sea of Galilee, Israel (Yoram Rozen, Technion, Physics Department, Haifa 32000, Israel or Yoram.Rozen@cern.ch)