satellite laser ranging under the Crustal Dynamics Project. In SLR the time required for a laser burst's roundtrip between the ground and a reflector-equipped satellite is used to determine the site's location. The errors in SLR are generally thought to be larger and more poorly understood than in VLBI, due in part to the use of a single satellite, decimeter errors in estimates of the position of the satellite, and the nonsimultaneity of observations. But what SLR lacks in precision it at least partially makes up for by the large number of sites in operation and the ability to determine distances between all sites in the network.

Demos Christodoulidis of NASA's Goddard Space Flight Center in Greenbelt, Maryland, and his colleagues report that five of six observed average plate motions determined between the North American, Pacific, and Australian plates are in general agreement with the geologic rates (*4*). One of the most clear-cut agreements is in a closing rate averaged from four lines between the Australian and Pacific plates of 4.6 ± 0.9 centimeters per year versus the geologic rate of 6.0 centimeters per year. The best SLR determination of plate motion comes from Southern California where the observed rate of motion between the North American and Pacific plates along the San Andreas fault is 6.1 ± 2.5 centimeters per year versus the geologic rate of 5.8 centimeters per year.

Once geodesists are quite sure that they are detecting real motion, they will be comparing it with geologic rates, which are averaged over at least 100,000 years. Then they will collect rates between and within as many plates as possible in order to pin down the modern forces that now jostle the plates, build mountains, and trigger earthquakes.

—RICHARD A. KERR

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WIMP's, Cosmions, and Solar Neutrinos

The same mysterious particles that dominate the evolution of the universe may also lurk in the core of the sun

The same weakly interacting, massive particles—WIMP's—that are thought to comprise the mysterious dark matter in the universe, and that perhaps triggered the formation of the galaxies (*1*), now seem to offer an elegant explanation for the solar neutrino problem.

Nearly two decades old, the solar neutrino problem rests on a sharp contradiction between theory and experiment. On the one hand, the standard astrophysical models of the sun predict that nuclear reactions in the core will release swarms of neutrinos at a certain, calculable rate. These neutrinos will then stream freely through the sun's outer layers and, in principle, will be detectable on the earth. On the other hand, a solar neutrino detector developed by Brookhaven National Laboratory's Raymond Davis has operated since 1968 in South Dakota's Homestake gold mine and has consistently measured a neutrino flux only one-third of the predicted value.

Over the years this neutrino deficit has become a major embarrassment for the theorists. Their standard model of the sun is based on well-understood nuclear physics, and has been very successful in relating the mass and composition of the sun to its luminosity and lifetime. So almost anything they do to damp out the neutrino production has to leave those predictions unchanged, which turns out to be extremely difficult. Indeed, their struggles have led them down some bizarre pathways. One hypothesis has it that a black hole has fallen into the center of the sun and will eventually cause the sun to collapse on itself. Another says that the sun has somehow turned off inside, and that the outer parts are only just beginning to cool.

Thus the appeal of WIMP's: they suppress the solar neutrinos without substantially altering the standard models of the sun.

The key idea was actually first noted in 1978 by astrophysicist John Faulkner of the University of California, Santa Cruz, and his graduate student Ronald Gilliland, now at the National Center for Atmospheric Research in Boulder, Colorado. They started from the fact that the Homestake detector is sensitive only to relatively high energy neutrinos produced by a certain rare reaction involving boron-8. This reaction in turn is very sensitive to temperature, so that the neutrino production tends to be highly concentrated at the center of the sun where temperatures reach their peak. In fact, in the standard solar models roughly 70 percent of the detectable neutrinos are produced within the central 5 percent of the radius, whereas less than 10 percent of the sun's luminosity is produced there.

Faulkner and Gilliland's idea was thus to postulate a haze of WIMP's orbiting almost freely in the core of the sun. In particular they were thinking of massive neutrinos left over from the big bang, which were then quite fashionable in cosmological circles. But in any case, if these hypothetical particles had the right mass—roughly 5 GeV—and if they interacted often enough with the ordinary nuclei—say, once every orbit or so—they could pick up energy at the center and distribute it throughout the core, thereby smearing out the temperature peak and damping the solar neutrino production *without* having any significant effect on the luminosity. Indeed, Faulkner and Gilliland's calculations showed that the energy transport would be quite efficient, so that only a relatively small number of WIMP's would be needed.

Unfortunately, big bang neutrinos in the 5 GeV mass range seemed to be ruled out from other cosmological evidence. Thus, unwilling to add to the list of "obviously crazy" solutions to the solar neutrino problem, Faulkner and Gilliland let the idea go by with only a brief mention in another paper (*2*).

Recently, however, the idea has been revived quite independently by William H. Press and David N. Spergel of the Harvard-Smithsonian Center for Astrophysics, who were inspired by the increasingly strong evidence that WIMP's play a major role in cosmic evolution, and by the plethora of new WIMP candidates being hypothesized by the particle physicists (*3*). (Actually, Press and Spergel prefer the name "cosmions".) In the process, the Harvard researchers have also pointed out a natural mechanism for getting the cosmions into the sun. Assuming that these are the particles that comprise the galaxy's dark mass halo, they argue, swarms of them will constantly be passing through the sun. Whenever one of them collides with a particle of ordinary matter, it will tend to lose most of its kinetic energy and go into orbit in the interior. Thus, over the 4.6-billion-year lifetime of the sun, the cosmions must have accumulated into just the kind of haze that Faulkner and Gilliland originally suggested. Indeed, the picture is remarkably consistent: if the cosmion collision cross section is the right order of magnitude for efficient thermal transport in the sun (roughly 10^{-36} square centimeter), then the present density of cosmions in the sun can be calculated—and it works out to one part in 10^{-12}, exactly what is needed for suppressing neutrino production to the observed levels.

With this encouragement, Faulkner and Gilliland have returned to the problem (*4*), and are currently collaborating with Press and his co-workers on a detailed and self-consistent calculation of the suppression effect.

Unfortunately, there does remain one dark cloud. The most obvious and plausible candidate particle is the photino, which is the hypothetical partner of the photon in the popular theory of supersymmetry. But it does not quite seem to work. The problem is that the photinos, if they exist at all, tend to annihilate each other when they meet. (More precisely, the photino is its own antiparticle.) This annihilation process means that they could never accumulate in the sun to the levels just mentioned. In fact, the upper limit on the density works out to be three or four orders of magnitude too low to affect the solar neutrino problem.

Since the same problem plagues many of the other plausible candidates, the cosmion/WIMP solution to the solar neutrino problem has to be rated as little more than an intriguing suggestion. On the other hand, its internal consistency and its relationship with other cosmological phenomena make it particularly attractive. And given the current state of particle physics, it is always possible that the cosmion particles, when and if they are ever observed in the laboratory, will have exactly the properties they need.—**M. Mitchell Waldrop**

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Fixing Nitrogen Without Molybdenum?

The metal molybdenum has for many years been considered a sine qua non for biological nitrogen fixation, the reduction of molecular nitrogen to ammonia by soil- and water-dwelling microorganisms. A variety of evidence indicates that the metal is part of the catalytically active site of nitrogenase, the enzyme that performs the reduction. Perhaps not surprisingly then, when Paul Bishop of North Carolina State University in Raleigh first proposed about 5 years ago that the bacterium *Azotobacter vinelandii* has an alternative system for fixing nitrogen—one that may not require molybdenum—the suggestion was greeted with more than a little skepticism.

However, recent research by Bishop and his colleagues and also by investigators from the Agriculture and Food Research Council Unit of Nitrogen Fixation at the University of Sussex, England, has confirmed that *A. vinelandii* has a second nitrogen-fixing system. As Christine Kennedy of the Sussex group told participants in the Sixth International Symposium on Nitrogen Fixation,* "Work of the past year has established that the alternative system is a reality."

Much of the recent evidence comes from studies of *A. vinelandii* mutants in which the genes coding for the nitrogenase proteins were specifically deleted or inactivated. If the bacterium had only the conventional nitrogen-fixing system, the mutants ought to lose the ability to reduce nitrogen, but this is not the case. For example, Bishop with Robert Eady of Sussex, found that a mutant in which all three nitrogenase structural genes had been deleted carries out the nitrogen-fixing reactions about as effectively as the wild type bacterium, but only when deprived of molybdenum. In contrast, the wild type must have the metal in the culture medium if it is to reduce nitrogen.

These results and others indicate, Bishop says, that the alternative system is activated in *A. vinelandii* by molybdenum starvation. The system may be an adaptation to molybdenum-poor soils. How widespread it is among nitrogen-fixing organisms remains to be determined.

The Bishop group is working to identify the enzymes that participate in the alternative pathway. Normal nitrogenase has two protein components. The molybdenum-iron protein contains both metals and reduces nitrogen with electrons transferred to it by the second protein, which contains only iron. The *A. vinelandii* deletion mutant lacks both of these, but Bishop and John Chisnell, also of North Carolina State, find that it has two new proteins that work together to reduce nitrogen. The larger one may play a role analogous to the molybdenum-iron protein, Bishop suggests. Although physiological studies indicate that molybdenum does not participate in nitrogen reduction by the alternative pathway, purification and analysis of the protein will be necessary to confirm that it does not contain the metal. The smaller of the two new proteins may be the equivalent of the iron protein.

The genes that code for the enzymes of the alternative system are also being sought. Robert Robson of the Sussex group has found that another *Azotobacter* species, *A. chroococcum*, has at least two versions of the *nifH* gene, which codes for the iron protein. One is part of the conventional nitrogen-fixing system; it is located in a cluster with the genes for the molybdenum-iron protein. The second *nifH* gene, which is about 90 percent identical to the first, is not a part of that cluster and may be involved in some fashion in the alternative system. Nevertheless, its role is unclear.

Although the Bishop group has evidence that the second *nifH* is transcribed into messenger RNA in *A. vinelandii* in response to molybdenum deficiency, it apparently does not code for either of the alternative nitrogenase proteins identified by Bishop and Chisnell. *Azotobacter vinelandii* may contain yet a third *nifH* gene.

The recent work has verified the existence of the alternative nitrogen-fixing system and shown that it is activated by molybdenum deficiency, but has left unanswered many questions about the operation of the system and its interaction with the con-

*The symposium was held at Oregon State University in Corvallis on 4 to 10 August.