Particle Physicists Look to the Heavens

The emerging discipline of particle astrophysics is aiming to shed light on the ghostly dark matter, the solar neutrino problem, and other cosmic mysteries

SCIENCE • IN THE • '90s

Sixth in a series

FOR THE BETTER part of a decade now, a small but steadily growing band of physicists have been turning away from the big accelerator experiments in favor of a loose-knit new hybrid discipline known as "particle astrophysics"—the application of elementary particle physics to the exploration of the cosmos. Their inspiration comes from some of the most nagging questions in astronomy: Is there something in the core of the sun that eats neutrinos? Is the x-ray source known as Cygnus X-3 bombarding Earth with bizarre, unknown particles? Are the galaxies really immersed in a sea of ghostly "dark matter"? And their experiments are now at a point where some answers could be in hand in the very near future. Indeed, one of the major scientific themes of the coming decade may well be a set of discoveries on a grand scale that will have come from students of the very smallest scales.

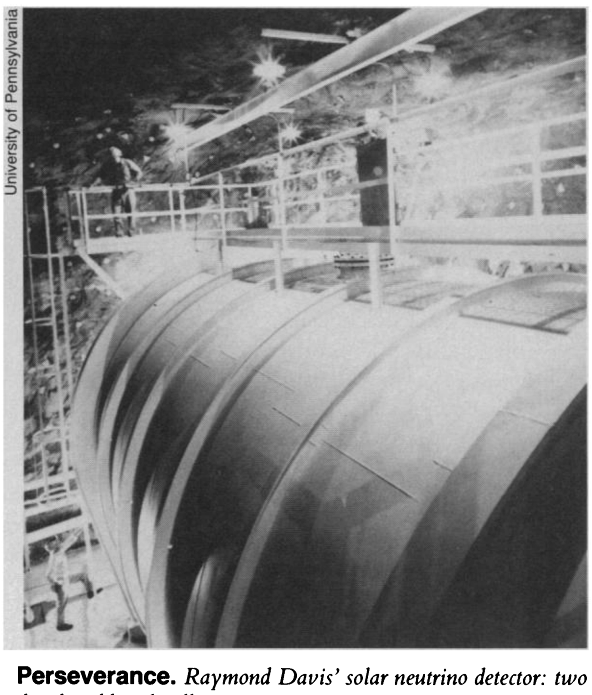
Particle astrophysics is "where some of the biggest advances are going to come," declares physicist David Caldwell of the University of California, Santa Barbara, who is himself working on dark matter detection.

"A large fraction of the particle physics community is beginning to get interested," agrees Bernard Sadoulet, director of the National Science Foundation's new Center for Particle Astrophysics at the University of California, Berkeley.

Particle astrophysics has not been without its birth pangs, of course. Even now, for example, the various discipline offices in the Department of Energy, the National Science Foundation, and other funding agencies are still at odds over just who should fund the field. Meanwhile, many U.S. practitioners worry about a loss of initiative to their European, Japanese, and Soviet counterparts.

Nonetheless, the field got an invaluable boost at the time of Supernova 1987A, when the IMB proton decay detector in Cleveland and the Kamiokande II proton decay detector in Japan simultaneously observed a burst of neutrinos that agreed precisely with the predictions of supernova theory. Even though these facilities had been built for another purpose entirely—the search for proton decay—that detection dramatized the possibilities of neutrino astronomy like nothing before or since.

Pending another supernova, however, the most promising experiments in particle astrophysics are those that are attempting to resolve the long-standing solar neutrino problem. The very existence of that problem is a testament to the perseverance of Brookhaven National Laboratory radiochemist Raymond Davis and his colleagues, who have spent the past 20 years monitoring the neutrinos produced by thermonuclear fusion reactions in the core of the sun. Davis's detector, located deep in the Homestake gold mine below Lead, South Dakota, is essentially a 600-ton tank of chlorine-rich cleaning fluid. When neutrinos from the sun pass through the tank, they very occasionally interact with chlorine-37 atoms and convert them to radioactive argon-37 atoms, which are then chemically separated and counted in order to prove the passage of the ghostly neutrinos.



University of Pennsylvania

Perseverance. *Raymond Davis' solar neutrino detector: two decades old and still counting.*

The problem is that Davis has consistently detected only about a third the number of neutrinos predicted by theory, despite two decades spent trying to find some source of error in the experiment. Furthermore, the deficit has recently been confirmed by Japanese physicists working at their Kamiokande II proton-decay detector. Which means, according to Kenneth Lande of the University of Pennsylvania, a former accelerator physicist who has worked with Davis for years, that either the theorists' predictions of the neutrino flux is wrong, or else some fundamentally new physics is involved—something that could waylay neutrinos as they exit the sun.

What might this "new physics" be? One of the most popular proposals is the Mikheyev-Smirnov-Wolfenstein (MSW) theory, which was announced in 1986. The theory starts from the fact that three types of neutrinos are known, only one of which—the "electron" neutrino—is produced in the sun and is capable of triggering the chlorine-argon reaction used at Homestake. The theory shows how subtle interactions with ordinary matter on the way out of the sun could cause electron neutrinos to "oscillate," transforming themselves some fraction of the time into one of the other two types: the muon and tau neutrinos. Since Davis's detector would never see these types, the deficit would be explained.

Unfortunately, says Lande, this new physics can't be put to the test by the chlorine experiment. That experiment is sensitive only to the highest energy solar neutrinos, which are produced by a rare fusion reaction involving the nucleus boron-8. A much better test would be to look at the lower energy neutrinos produced in proton-proton fusion, the overwhelmingly dominant source of the sun's energy. If those neutrinos are also depleted, he says, then you have no choice but to believe in some version of the new physics.

So how do you measure the low-energy neutrinos? Davis, Lande, and their colleagues came up with the principle as early as 1974. The idea was to use a mass of gallium, whose stable isotope gallium-71 can absorb a low-energy neutrino and produce a radioactive isotope, germanium-71. There was one big drawback, though: gallium is rare and expensive. When Lande, Davis, and their colleagues asked what is now the Department of Energy for 50 tons of gallium, the proposal got nowhere.

As a result, says Lande, a group of German scientists who had offered to collaborate on the experiment, and to put up 25% of the money as well, went off to seek European collaborators. The end product was Gallex, an experiment now scheduled to begin operation with 30 tons of gallium late this year in the Gran Sasso highway tunnel in Italy. In the meantime, the Soviet Academy of Science's Institute of Nuclear Physics invited Lande, Davis, and a number of other U.S. scientists to join in a 60-ton Soviet-American Gallium Experiment (SAGE) in a mine in Baksan.

For Lande, the fact that the experiment is being done elsewhere still stings. "We blew that one completely," he says. But the fact is that the experiments are finally getting done. Optimists speculate that the first results from SAGE could come as early as June 1990, at the Neutrino '90 meeting in Geneva. Results from Gallex should be forthcoming within a year or so thereafter.

If the gallium results do confirm the need for new physics, the matter will hardly end there. A whole new generation of solar neutrino observatories will be needed to analyze the effect in detail. Some of those projects are already under way, a prime example being the Sudbury Neutrino Observatory (SNO), a joint project of Canada, the United States, and the United Kingdom. Recently given a go-ahead by the Canadian government and scheduled to come on line in 5 to 6 years, SNO will contain 1000 tons of heavy water (deuterium oxide) in a tank located 2 kilometers below ground in a nickel mine near Sudbury, Ontario. It should give researchers a detailed spectrum of the solar neutrinos at all energies, which should in turn allow them to put the various theories to a rigorous test. And because it is designed to detect *all* neutrinos, not just the electron type, it should also provide a stringent test of the MSW oscillation theory: if any electron neutrinos have oscillated away, SNO should see a corresponsing enhancement of muon and tau type neutrinos.

If the solar neutrino experiments offer the near certainty of interesting results, the cosmic ray studies offer a different aspect of particle astrophysics: the romance of the unknown. The mystery arose in 1983, when physicists working with an array of cosmic ray detectors in Kiel, West Germany, observed a series of high-energy cosmic ray events coming from the direction of the celestial powerhouse known as Cygnus X-3. They were astonished. Objects like Cygnus X-3 are not uncommon in the galaxy; each one consists of a more or less ordinary star in close orbit around a small, ultradense neutron star, which pulls streamers of gas across the gap and accelerates them toward its surface with near thermonuclear force. To see one as a specific source of cosmic rays, however, was almost unprecedented.

That was not the only perplexity. The Kiel physicists had no direct way of knowing what the original cosmic ray particles from Cygnus X-3 had been, since all they actually detected were showers of particle debris produced when the cosmic rays struck atoms high in the atmosphere. Nonetheless, a variety of astrophysical arguments convinced them that the only known cosmic ray particles that could fit the data were gamma rays. The problem was that the showers were rich in the short-lived particles known as muons—and gamma rays almost never produce muons.

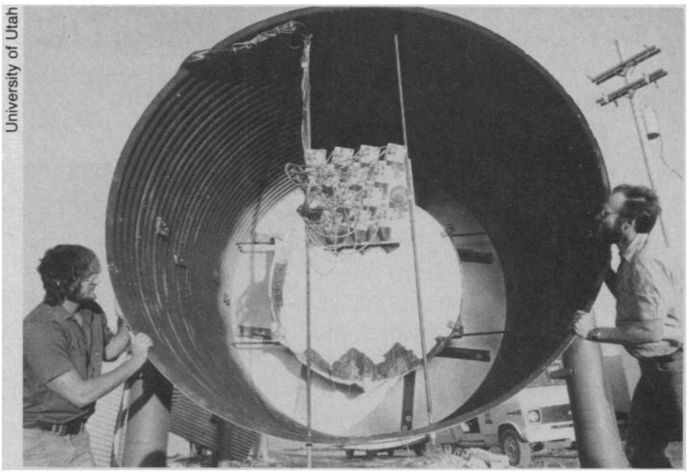
The news created a sensation among particle physicists, says University of Utah cosmic ray researcher Steven Corbato, especially after similar signals were seen elsewhere. "Either gamma rays at those energies are behaving like hadrons," he says, using the name of the generic class of particles that include neutrons and protons, and that *can* produce muons, "or there exists a new neutral particle that has not been discovered in our accelerators—even though it should have been."

The very idea "precipitated a big rush into the field by high-energy physicists," says Corbato's Utah colleague Brian Newport. "Little arrays started popping up all over. There was an enormous furor between those who 'saw' it, and those who didn't." Did a failure to confirm the effect mean that it didn't exist? Or did it simply mean that Cygnus X-3, which is known to be highly erratic as an x-ray source, wasn't "on" at the time? Part of the problem, says Corbato, is that the earlier detections were always on the ragged edge of statistical significance.

But this may have just begun to change. Trevor Weekes and his colleagues have recently used their detector array at the Whipple Observatory in Arizona to compile some very good statistics. They saw one cosmic ray source quite clearly—the nearby pulsar in the Crab nebula—and nothing else. Moreover, the Crab seemed to be emitting perfectly normal gamma rays.

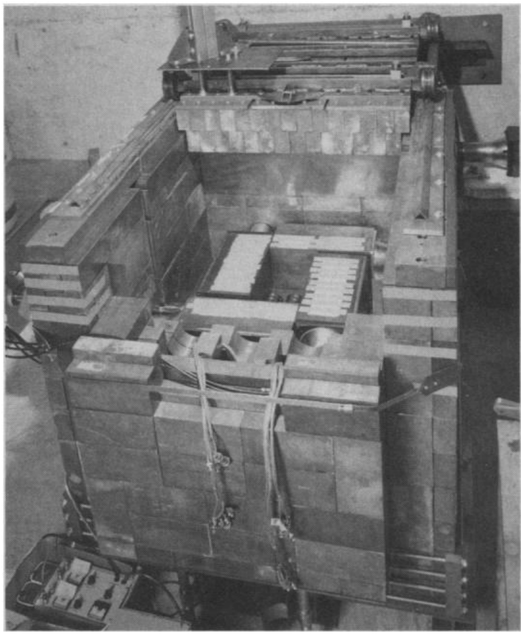
That result might lead one to think that, as Weekes says, "Cygnus X-3 is fading into the mist." But the controversy is far from dead. An enhancement of ultrahigh-energy cosmic rays from the direction of Cygnus X-3 has recently been detected by Utah's own Fly's Eye II facility, a unique array of telescopes that watch for the brief pulses of fluorescent light produced by the cosmic rays in the atmosphere.

Mercifully, the reign of ifs, buts, and maybes seems to be approaching an end. Out at the Fly's Eye II site on the Dugway Proving Grounds near Salt Lake City, the Utah physicists and their colleagues are deploying the most potent assemblage of cosmic ray detectors in the world. The University of Michigan had already installed the world's largest array of underground muon detectors there. And on the sagebrush desert directly above, a band of graduate students and postdocs working under University of Chicago Nobel laureate James Cronin is scattering a dense network of detectors for the $3-million Chicago Air Shower Array. There are currently 529 detectors in place,



University of Utah

Fly's Eye. *Preparing to watch for cosmic ray fluorescence in the atmosphere, University of Utah researchers inspect one of the array's 67 telescopes.*



Lawrence Berkeley Laboratory

In search of dark matter. *The Berkeley–Santa Barbara detector waits . . . and waits.*

with the full array of 1089 detectors scheduled for completion in 1991.

By combining the data from these two facilities, says Newport, not to mention the Fly's Eye and several other prototype detectors at the same site, the payoff should be at least an order of magnitude increase in sensitvity over any previous cosmic ray arrays. "Either we get a strong result, or we don't," he says; either way, the controversy will be resolved.

And then there's dark matter. If the cosmic ray work is a long shot, the search for dark matter is the longest shot of all. Most astronomers believe that the dark matter exists, even though it is utterly invisible: the observations show that, without an all pervasive something to hold things together by gravity, individual galaxies and even whole clusters of galaxies would simply fly apart. Indeed, dark matter seems to account for 90 to 99% of all the mass in the universe.

These days the favorite explanation for dark matter is that it is a haze of massive elementary particles left over from the Big Bang. Theoretical physicists have proposed a whole menagerie of hypothetical particles that could fill the bill. However, one crucial characteristic of these particles is that they would interact very, very weakly with ordinary matter—which is why no one has noticed them before now. So even if they do exist, detecting them will be an extraordinary challenge.

But then, a challenge like that makes some people try all the harder. Starting from the vaguest ideas in the mid-1980s, a number of experimental approaches have now built up impressive momentum. The NSF's late 1988 decision to devote one of its series of science and technology centers to the dark matter problem—the $1.8-million center in Berkeley—was a recognition of a movement that was already well under way.

"Currently the main experimental effort is in ionization detectors," explains Santa Barbara's Caldwell, a collaborator with Berkeley's Sadoulet and the Lawrence Berkeley Laboratory's Fred S. Goulding on perhaps the most successful such detector. The idea is to take a very pure crystal of a semiconductor such as silicon or germanium, shield it very, very carefully from cosmic rays and radioactive trace elements—and watch. Any dark matter particle passing through the crystal should occasionally knock loose an electron, which would flow through the crystal into electronic detectors.

"These detectors have been able to eliminate an extremely large range of possible particle masses and cross sections [a measure of reaction probability]," says Caldwell. Unfortunately, however, there is a whole class of dark matter candidates that interact so weakly that the ionization detectors can't hope to touch them. Among them are most of the theorists' favorites, including a bevy of hypothetical "supersymmetric" particles such as the photino, the Higgsino, and the Zino. For these, he says, "a cryogenic detector is necessary."

And what is a cryogenic detector? The idea is to take a large crystal of some suitable material, cool it as close as possible to absolute zero, shield it even more carefully than before, and, once again, watch. This time, however, the signal would be the absorption of a dark matter particle by a single nucleus. The recoil of the nucleus would set up a shock wave, or "phonon," in the crystal, which should in principle be observable.

In practice, the phonon would be extraordinarily feeble; any such experiment would stretch the state of the art to the breaking point. And yet several groups think they can do it. At Stanford, for example, physicist Blas Cabrera plans to watch the outside of a crystal in hopes of detecting the pattern of vibration set up as the shock wave strikes the crystal surface. Other groups are looking at various ways to detect the infinitessimal rise in temperature as the phonon dissipates its energy.

Several prototypes have already been demonstrated, and if all goes well, the first full-scale cryogenic detectors could be up and running in 2 to 3 years. Indeed, the pace seems to be accelerating, not least because many physicists are interested in the technology of ultralow background, ultrasensitive detectors for its own sake. Moreover, as Institute for Advanced Study theorist David Spergel points out, "the European groups have a lot more money and people working on this than we do."

Spergel's comment once again raises the bitter plaint of the U.S. particle astrophysics community: that the U.S. funding agencies have not made the shift to particle astrophysics nearly as fast as the physicists have. The problem is not so much a lack of money (these experiments tend to be modest in cost compared to what goes on at the big accelerators), but the structure of the bureaucracy. The new field hasn't found an institutional home, so it isn't really anyone's responsibility. "Individual people at the funding agencies have been very supportive," says Spergel. "But the particle physicists say, 'This is wonderful stuff—we're really happy to have the astronomers pay for it,' " etcetera.

At the Department of Energy, particle physics research head P. K. Williams bristles a bit at that characterization. "If it's high energy physics and it's excellent science, we support it," he declares. And indeed, what the department calls "non-accelerator physics" has been getting increasing attention of late. But the experiment does have to be something that furthers *particle* physics, he concedes, not astronomy.

On the other hand, as even the most ardent practitioners of particle astrophysics have to admit, the funding prospects in the United States have been getting brighter and could catch fire—if only . . . say, dark matter is discovered, or the oddball particles from Cygnus X-3 are verified, or the MSW mechanism is confirmed, or more supernova neutrinos start showing up at SNO and elsewhere.

And if none of those things happens, all the money in the world won't make any difference. "Particle astrophysics is a place to make some good bets," says John Bahcall of the Institute for Advanced Study, chairman of the National Academy of Sciences' new astronomy survey panel. "But whether it lasts as an independent field depends upon what's found."

■ M. MITCHELL WALDROP