PARTICLE ASTROPHYSICS

A symbiosis is evolving: Astrophysical observations are elucidating the nature of the elementary particles, while particle theory and experimental techniques address the dark as well as the showy components of the cosmos, and how it all began.

Bernard Sadoulet and James W. Cronin

Particle astrophysics emerged in the 1980s as a new field at the junction of high-energy astrophysics, cosmology and particle physics. This new experimental, observational and theoretical discipline concerns itself, for example, with the nature of dark matter; the detection of neutrinos from the Sun and from supernovae; the evidence for powerful acceleration mechanisms in the vicinity of neutron stars; and the suggestion that quantum fluctuation and topological singularities in the first moments of the cosmos played a role in the formation of the great structures we see today stretching over hundreds of millions of light-years.

The extensive-air-shower array shown in figure 1, recently built in Dugway, Utah by a Chicago–Michigan collaboration, illustrates the symbiosis of particle physics and astronomy. This ground array of 1089 scintillators looking for stellar sources of 10^{14}-eV gammas is studded with underground muon detectors that serve to distinguish gammas from protons and other cosmic-ray hadrons. Thus they can also look for possible anomalous hadron-like behavior when these ultrahigh-energy gammas hit the atmosphere.

Although particle astrophysics received some consideration in the previous surveys of astronomy and astrophysics, the present survey is the first to avail itself of a special panel on particle astrophysics. This panel was assigned three subfields: particle physics and cosmology; particle physics and the physics of stars; and high-energy astrophysics, including, for example, the presence of ultrahigh-energy gammas in cosmic rays.

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Particle physics and cosmology

The physics of the early universe is intimately related to particle physics at the very highest energies,[1] and it is not possible to distinguish between them in the quest for the answers to the fundamental questions of cosmology: What is the character of the ubiquitous dark matter? How did matter come to predominate over antimatter? How did the universe get to be so smooth, so flat and so old? On the other hand, it's not all that smooth. What is the origin of the inhomogeneities that triggered the eventual formation of galaxies?

Cosmological observations, in turn, provide essential constraints in the construction of unified theories in particle physics. Such observations may be our only source of information about physics at the very high energies (10^{25} eV!) where the unification of the different classes of particle interactions is expected to become manifest.

The dark-matter question is, at the moment, the best example of the interdependence of particle physics and cosmology. From decades of astronomical observations we are quite confident that most of the matter in the universe is nonluminous and transparent. Various cosmological arguments suggest that the dark matter may not be ordinary baryonic matter (neutrons and protons). If not baryons, it may be that dark matter consists of relic particles from the early phases of the universe. The

Extensive air shower array in Dugway, Utah, was recently completed by a Chicago–Michigan collaboration. Its 1089 scintillators arrayed on the ground to look for particle showers from cosmic-ray gammas exceeding 10^{14} eV are supplemented by underground muon detectors to distinguish gammas from protons and to look for anomalous hadron-like behavior by ultra-energetic gammas. **Figure 1**

theorists have three leading candidates: light neutrinos, axions and "WIMPs" (weakly interacting massive particles).[2,3]

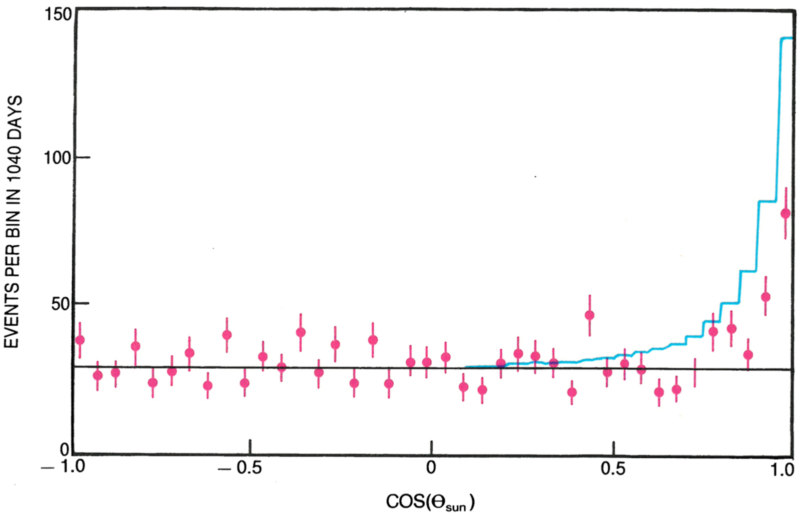
Just as there is a cosmic background of photons with a 2.7 K blackbody spectrum, there is a similar cosmic background of low-energy neutrinos. The upper limit on the mass of the electron neutrino nowadays is about 10 eV. But if any one of the three known neutrino species had a mass of about 30 eV, such a "light" neutrino would account for all the dark matter the cosmologists want. Because no viable method has yet been devised to detect the cosmological neutrinos directly, we will have to look in the laboratory for nonvanishing neutrino masses.

The hypothetical axion, a very light (mass of about 10^{-3}–10^{-6} eV) pseudoscalar particle, was invoked by theorists to keep *CP* symmetry violation out of the strong interactions of the elementary particles. The interactions of axions with conventional matter would be only slightly stronger than gravitational. Nonetheless, experimenters have already achieved sensitivities within a factor of 300 of what one would need to see axions.

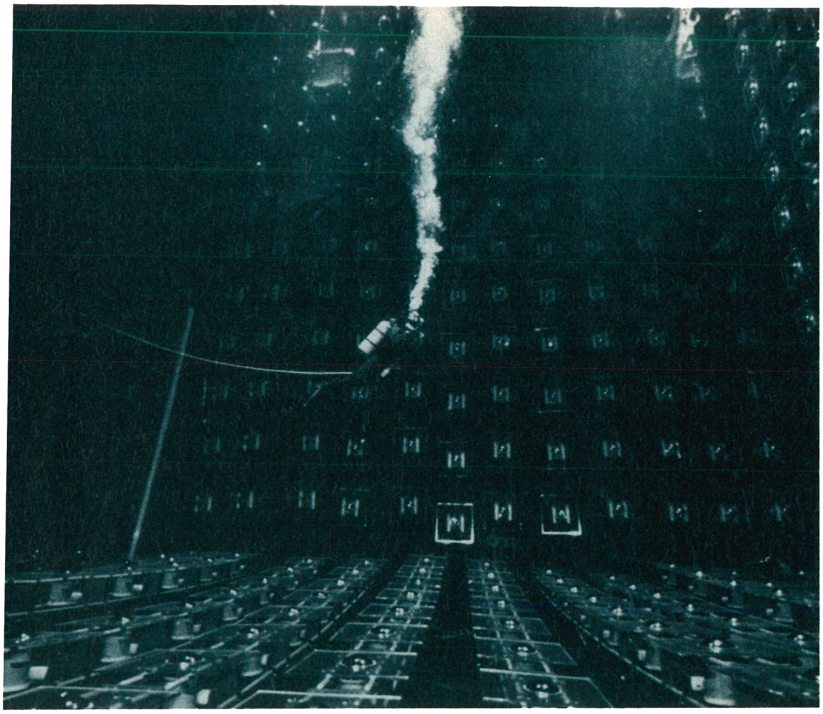
WIMPs are a general class of much heavier dark-matter candidates. They are imagined to have been in thermal equilibrium with the rest of the matter in the early universe. If the abundance of WIMPs provides just the dark-matter density the cosmologists favor, it turns out that their interaction cross sections would have to be about the same as those of the ordinary weak interactions. This similarity may be just a coincidence, or it may be a precious hint that physics at the 100-GeV mass scale of the vector bosons that mediate the weak interaction (W^+, W^- and Z^0) may also be responsible for dark matter! For instance, dark matter may be made of heavy neutrinos or of "neutralinos," a stable species predicted by the "supersymmetric" theories.

It would be possible, in principle, to detect WIMPs directly by the recoil when they scatter off a nucleus in a laboratory target. This would require very sensitive detectors with excellent rejection of radioactive background. Present-day detectors using ionization techniques have already set interesting limits that exclude the possibility that dark matter is made of heavy neutrinos of the conventional Dirac type.[4] But before they can look for neutralinos, experimenters will have to improve the rejection of background by two or three additional orders of magnitude. That may eventually be accomplished with emerging technologies based on the detection of phonons or other excitations in superconductors.[2] There have recently been encouraging results with small cryogenic detectors. It might also be possible to ferret out exotic dark-matter particles in our Galaxy by the looking for more conventional products of their annihilation or decay.

Other speculative relic particles may be significant in cosmology even if they do not fit the requirements for dark



Angular distribution, relative to the direction of the Sun, of incident neutrinos recorded[7] by the Kamiokande II solar-neutrino detector in Japan from 1987 to 1990. The peak in the direction of the Sun was the first direct evidence that it is indeed a source of neutrinos. Above the isotropic background (black line) one sees only about half as many neutrinos in the peak as predicted by the standard solar model (blue line). **Figure 2**



Two thousand phototubes staring at 8000 tons of water in the Irvine–Michigan–Brookhaven detector for five years never did see the Čerenkov light from the proton decay they were looking for. But then in February 1987, by sheer serendipity, the IMB detector recorded a burst of neutrinos from the first supernova visible to the naked eye in four centuries. The photo shows a diver doing maintenance. **Figure 3**

matter. Magnetic monopoles, for example, are being looked for by MACRO, a football-field-sized detector in the underground laboratory beneath the Gran Sasso d'Italia in the Abruzzi Apennines.

The physics of particles and stars

Stellar astrophysics is also intricately bound up with particle physics. Neutrinos, for example, are copiously produced in stars and in supernova explosions. They can be detected by techniques, and even facilities, borrowed from particle and nuclear physics. The relationship is symbiotic, providing essential information to the astrophysicist while offering the particle physicist a unique opportunity to study the neutrino itself.

Solar neutrinos. Solar physicists believe they understand the nuclear processes that produce energy in the Sun's interior well enough to calculate the resulting spectrum of solar neutrinos with some confidence.[5] For the last 20 years a radiochemical experiment has been running deep inside the Homestake gold mine in South Dakota.[6] (See PHYSICS TODAY, October, page 17.) The experiment looks for radioactive argon nuclei created by energetic solar neutrinos hitting chlorine nuclei in a 600-ton vat of cleaning fluid. The great puzzle is that the Homestake detector sees less than a third of the flux predicted by the "standard solar model." This deficit has recently been confirmed by a Japanese–American collaboration operating a detector in the Kamioka lead–zinc mine in Japan.[7] The Kamioka detector, which began life searching for proton decay, is a large vat of water monitored by phototubes to detect the Čerenkov radiation from recoil electrons elastically scattered by solar neutrinos. (See figure 2.)

"The solar neutrino problem," as this discrepancy between calculated and observed fluxes is called, may be telling us that processes in the solar interior are different from our expectations, especially the relatively rare nuclear processes responsible for the high-energy end of the neutrino spectrum visible to the Homestake and Kamioka experiments. On the other hand, our ignorance may be mistaking not the *production* of solar neutrinos, but rather their journey from the solar core to the terrestrial detector. If, for instance, neutrinos have a nonvanishing mass, the observed flux deficit may be due to the transmutation of electron-type neutrinos into another neutrino "flavor."

To distinguish between an astrophysical and a particle physics origin of the deficit, it is necessary to measure the copious flux of the lower-energy neutrinos produced in the principal proton–proton fusion reaction in the solar core, about which the standard solar model brooks no ambiguity. Unfortunately the upper energy limit of these all-important p–p neutrinos is 0.42 MeV, far below the sensitivity threshold of the chlorine and water Čerenkov detectors.

Two gallium experiments just getting under way should be able to do the trick: a Soviet–American effort in the Baksan underground laboratory in the Caucasus and the European GALLEX collaboration at the Gran Sasso Laboratory. The Baksan group recently presented tantalizing preliminary results, suggesting that the neutrino deficit *is even worse* at low energy. This new result, if confirmed, would indicate that the solution of the puzzle lies in the oscillation of neutrinos between different flavors.

A second-generation water Čerenkov experiment on a grand scale has just been approved. At the Sudbury Neutrino Observatory, in a deep mineshaft 200 miles north of Toronto, a Canada–UK–US collaboration is building a detector that will use a kiloton of *heavy* water. In addition to measuring the elastic scattering of electron neutrinos off electrons with high efficiency, this experiment will also record neutrinos of other flavors as they break deuterons apart.

Supernovae. The most significant event in establishing neutrino astronomy was quite serendipitous. The first supernova visible to the naked eye since the invention of the telescope occurred in 1987 while two water-Čerenkov experiments just happened to be looking for proton decay. And both of them (Kamioka[8] and the Irvine–Michigan–Brookhaven detector[9] in a salt mine on the shore of Lake Erie, shown in figure 3) detected a handful of neutrinos from the supernova explosion. The observed fluxes were compatible with theory—an impressive confirmation of our understanding of supernovae.

If the Sudbury Observatory or a similar facility is still in operation the next time there's a supernova (visible or invisible) in our Galaxy, it should be able to detect thousands of neutrino events from the explosion. That would make it possible to study the time dependence of neutrino emission from the collapsing stellar core and to establish an upper limit of perhaps 100 eV on the masses of the mu- and tau-type neutrinos.

High-energy astrophysics

High-energy astrophysics is also directly linked to particle physics. On the one hand, particle-physics techniques extend the observation of astrophysical neutrino sources and cosmic radiation to higher energies, providing clues to the celestial accelerating mechanisms. (See the article by Christopher McKee and William Press on page 69) On the other hand, the extraordinarily high particle energies found in cosmic radiation (up to 10^{20} eV) may provide information about particle interactions at energies that no conceivable man-made accelerator could approach.

Gammas. Orbiting instruments have given us considerable coverage of the x-ray and gamma regimes. But above 10^{10} eV, the gamma fluxes are too small to be seen by telescopes of the size that can be put in orbit. Fortunately, at 10^{11} eV cosmic gammas begin to produce atmospheric showers sufficiently intense to be detected by instruments on the ground.

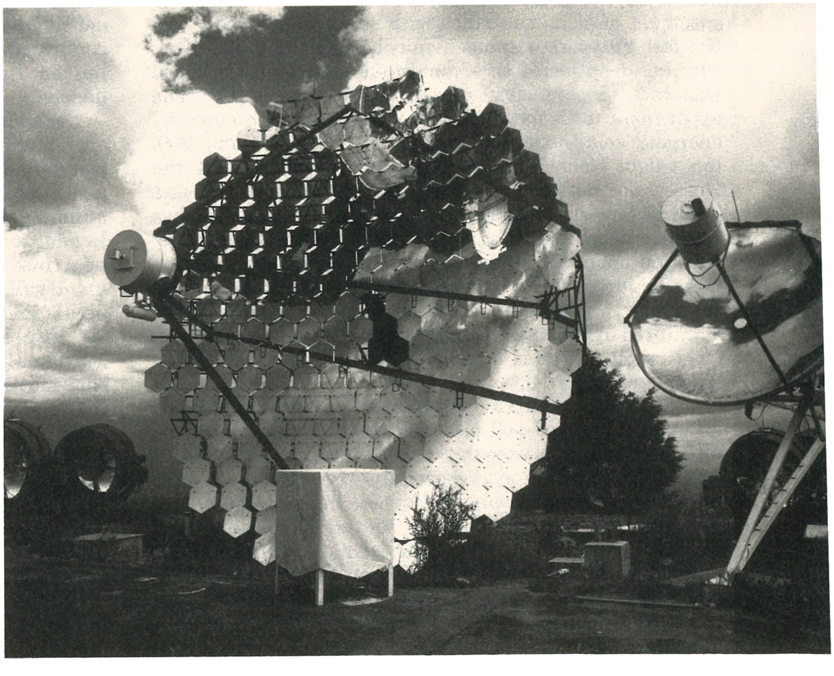
Two basic techniques are available.[10] (See PHYSICS TODAY, November 1988, page 17.) If the energy of the primary cosmic-ray gamma is less than about 10^{13} eV, the shower dies out in the upper atmosphere, but its Čerenkov light can be observed with specialized telescopes with phototubes. This technique has now reached maturity with the detection of 10^{12}-eV gammas from the Crab nebula by the Whipple Observatory's 10-meter Čerenkov telescope, shown in figure 4.

Above 10^{14} eV, enough shower particles reach the ground to make large arrays of detectors useful. Typically one has an array of 1-m^2 plastic scintillators on the ground, spaced about 10 or 20 meters apart. This is a venerable technique for the study of high-energy cosmic rays. In the early 1980s cosmic-ray groups at Leeds reported[11] an excess of air showers with energy greater than 10^{15} eV from the direction of the x-ray binary Cygnus X-3. Cosmic rays from a point source would, of course, have to be neutral: The magnetic field of the Galaxy would scramble the direction of charged particles. These provocative observations stimulated the construction of larger arrays dedicated to the search for point sources of cosmic rays. Prominent among these are the Cygnus array at Los Alamos, completed in 1987, and the just completed Chicago–Michigan array in the high desert of Utah. With the exception of Cygnus group's reports[12] of bursts of radiation from the direction of the binary Hercules X-1, there have been no significant observations of point sources emitting gammas above 10^{14} eV since 1986. In the coming years these new arrays will search for such point sources with much improved sensitivity.

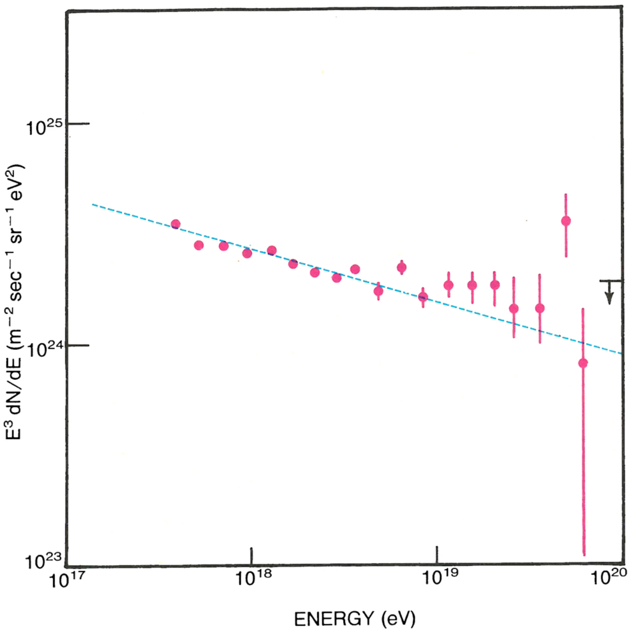
In addition to their frustratingly sporadic nature, the showers from the x-ray binaries present another quandary. The high-energy photons—if that's what they really are—appear to be strangely hadronic-like in the way they generate showers. They seem to make too many muons. If these elusive observations are borne out by the Los Alamos and Dugway ground arrays, it will mean either that the standard particle theory doesn't understand how photons interact with matter at these enormous energies, or that the primaries are not really photons but rather some exotic new species. Coming from a point source, as they appear to do, they couldn't be charged particles; but no neutral hadron we know of lives long enough for such cosmic journeys.

High-energy neutrinos may provide another window on astrophysical accelerators in the Galaxy. If, like high-energy gammas, they too are observed to come to us from point sources, that would give a clear proof that hadronic processes are playing an important role.

Neutrinos that pass through the Earth produce upward-going muons that could be recorded by suitable underground detectors. But the expected signals are so small that the detector area would have to be the size of several baseball fields. The DUMAND experiment off the coast of Hawaii represents a first attempt at exploring this



Čerenkov telescope at the Whipple Observatory on Mount Hopkins in Arizona. Its 10-meter array of reflectors and photomultipliers records Čerenkov light from air showers induced by cosmic-ray gammas heading toward the telescope with energies above 10^{12} eV. The Whipple group has detected such gammas coming from the Crab nebula. Evidence of other stellar sources is less conclusive, as is the observation that these showers may have anomalously hadron-like Čerenkov patterns. **Figure 4**



Energy distribution of cosmic-ray primaries (charged and neutral) with energy E exceeding 10^{17} eV, as measured by the Fly's Eye detector. At these extreme energies the shower excites enough fluorescence in the atmosphere to be seen by the detector's array of photomultipliers even when the primary is not heading toward the Fly's Eye. The dashed line, describing a power law, emphasizes the flattening of the spectrum above 10^{19} eV one would expect for extra-Galactic protons. **Figure 5**

virgin territory. Recently approved by DOE, DUMAND will be a floating Čerenkov detector anchored to the ocean floor. It should be sensitive enough to observe a few neutrinos from Cygnus X-3, *if* the gamma fluxes are indeed as high as the Kiel group reported in 1983.

Charged cosmic rays include, in addition to protons, the nuclei of all known elements, as well as electrons, positrons and antiprotons. Their energies are observed to range from 10^6 to 10^{20} eV. The study of this tenuous plasma of relativistic particles addresses questions closely related to most of the themes we have broached here.[13]

For charged particles up to 10^{14} eV, cosmic-ray measurements are best conducted above the atmosphere. The nuclear population distribution and energy spectra of cosmic rays give us important clues to the mechanisms of acceleration. The last decade has seen notable advances in our knowledge of cosmic-ray composition, particularly in the GeV region. The recent observation of a dependence of abundance on ionization potential indicates that *atomic* properties are important in the process that injects particles into the interstellar medium. These abundance measurements also yield important information about nucleosynthesis at various stages of the chemical evolution of our Galaxy. The decade has also witnessed great progress in determining the characteristic confinement times of cosmic-ray particles. From various radioisotope abundances one gets an average of about 10 million years. One finds somewhat more antiprotons and positrons than expected, prompting the interesting speculation that some of them are annihilation products of exotic dark-matter particles.

Above 10^{14} eV the flux of charged cosmic-ray primaries becomes too small for direct measurement in space. One has to resort to ground arrays to observe the extensive air showers generated by the primaries. The highest energy region is particularly interesting. The mere existence of 10^{20}-eV primaries is surprising: We know of no process that could plausibly be producing particles of such inordinate energies. Moreover, at 10^{19} eV the gyration radius of protons in the magnetic field of the Galaxy becomes comparable to the Galaxy's size. Therefore the field couldn't confine them for very long.

If, on the other hand, these very energetic protons are of extra-Galactic origin, their spectrum should have a sharp cutoff at 10^{20} eV because of pion production in collisions with the soft photons of the 2.7-K cosmic background. Below this cutoff there should also be a spectral flattening due to the pileup of debris from these collisions.

The University of Utah's Fly's Eye, now surrounded by the new Chicago–Michigan detector array, is looking for just such features. Its mosaic of mirrors and photomultipliers monitors the night sky for flashes of fluorescence from ultrahigh-energy protons and gammas. The Fly's Eye has recorded several hundred events of energy greater than 10^{19} eV. (See figure 5.) The spectrum thus observed[14] does indeed hint at a flattening above 10^{19} eV. Moreover, no event has been recorded beyond 10^{20} eV. All this suggests that these ultra-high-energy cosmic rays are extra-Galactic protons, but a definitive conclusion will require much higher statistics. The proposed new High-Resolution Fly's Eye would presumably do the trick.

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