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Neutrino Astronomy: A New Window on the Universe

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The human eye is a remarkable observational instrument. Through it we can marvel at the colors of a rainbow, the falling of a snowflake, or the flight of a comet across the sky. Yet despite its great sensitivity, the very nature of the eye places severe restrictions upon what we as humans can directly see. As a result, over the years many types of apparatus have been devised to help extend our vision into regions of the electromagnetic spectrum to which the eye does not respond. Through radiotelescopes, we have learned much about the nature of the universe that had been previously hidden from our view. Likewise, x-ray and gamma-ray astronomy are now providing new pictures of the cosmos.

Much information about the universe may be contained in a completely different form of radiation. Neutrinos are particles produced by the so-called weak interaction and as discussed below, are expected to be produced in a variety of astronomical environments. The neutrino interacts very feebly with matter, and as a result can literally pass through light years of rock without significant attenuation. For this reason, if we could " see " neutrinos, we could learn a great deal about previously obscurred regions of space. Through the use of techniques developed for nuclear and particle physics research, measurements of the numbers, energies, and arrival directions of neutrinos are beginning to produce valuable new information on a number of high-energy astrophysical processes.

Physics of Neutrinos

Because neutrinos are so penetrating, their detection is very difficult. Their existence was proposed by W. Pauli in 1930 in order to reconcile experimental results on beta decay with the firmly held ideas of the conservation of energy and of angular momentum. Beta decay is a type of radioactivity induced by the weak interaction. The decay of the free neutron is an example of this process. Numerous experiments demonstrate that the decay of the neutron produces a proton and an electron. If these were the only particles produced, the laws of conservation of energy and linear momentum require that the electrons should have a well-defined energy. As can be seen from Figure 1, however, experiments show that the electrons produced in such decays have a continuous spectrum of energies from zero up to the maximum value allowed by energy conservation. It is also known that the neutron, proton, and electron all have an intrinsic angular momentum of 1/2 $\hbar$ ($\hbar$ = Planck's constant/2π). According to the laws of quantum mechanics, two half-integer angular momenta cannot be combined to yield a half-integer. Thus in order to conserve energy, linear momentum, and angular momentum Pauli suggested that another particle must also be created in the process of beta decay. The experiemntal data requires that this particle must be uncharged, have angular momentum of 1/2 $\hbar$, and have small or zero mass. This object is the neutrino.

The direct detection of the neutrino was not accomplished for more than 20 years after Pauli's proposal. F. Reines, C. Cowan, and their collaborators observed reactor-produced (anti-) neutrinos through the inverse beta decay reaction

$$\text{proton} + \text{anti-neutrino} \longrightarrow \text{neutron} + \text{positron}$$

by detecting both the neutron and the positron. Since then neutrino-induced reactions have become a well-established branch of particle physics research. In fact, neutrino beams are now routinely available at a number of laboratories. An example of a high energy neutrino-induced reaction as photographed in a bubble chamber is shown in Figure 2.

It is now known that there are at least three distinct types (or flavors) of neutrinos: the electron-type, the muon-type, and the tau-type. For many years it was thought that rest mass of the neutrino was zero. However, recent attempts to combine the strong, weak, and electromagnetic interactions into one unified theory lead to the idea that the neutrino may have a small but finite mass. This has lead to speculations that neutrinos may occasionally make transitions from one type to another. Furthermore, if their mass is non-zero, neutrinos could provide the so-called "missing mass" required to close the universe. For these reasons there is currently a great deal of interest among both the astronomical and physics communities in the properties of neutrinos.

Astronomical Sources

The nuclear reactions that are the origin of stellar energies are also sources of neutrinos. Through both the proton-proton and CNO hydrogen-burning chains that occur in main-sequence stars, large numbers of relatively low energy (~1 million electron volts = 1 MeV) electron-type neutrinos are thought to be produced. Thus our Sun is believed to be a prodigious source of neutrinos. From the observed luminosity of the Sun, it has been estimated that the flux from the Sun at the Earth's surface is about 66 billion neutrinos per square centimeter per second ! If we could detect these neutrinos, we then would have direct evidence that our basic understanding of stellar energy generation is correct.

Sources of somewhat higher energy neutrinos are the violent deaths of massive stars known as supernovae. An example of a supernova explosion is illustrated in Fig. 3. It is generally believed that for stars whose masses are greater than or equal to about ten times that of the Sun, a sequence of nuclear burning stages eventually converts about 1.4 solar masses of core material into iron-group elements. Since these are the most tightly bound nuclei, no further energy-generating nuclear reactions are possible. Thus there is nothing to resist the mutual gravitational attraction of this matter, with the result that collapse of the core of the star occurs. During this collapse, the density of the infalling matter becomes so high that electrons are driven into nuclei and are captured by protons via the process:

$$\text{proton} + \text{electron} \longrightarrow \text{neutron} + \text{neutrino}\ .$$

The electron-type neutrinos produced via this mechanism are expected to have energies of about 10 - 20 MeV. The timescale over which they are emitted is thought to be only a fraction of a second during which about 10^{56} neutrinos are emitted. Just after this, a somewhat longer period of neutrino - anti-neutrino pair emission could produce an additional 10^{56} - 10^{58} slightly lower energy neutrinos (and anti-neutrinos). Thus a very short, but intense burst of such neutrinos from a well-defined direction in the sky could provide a means to detect supernova explosions that might otherwise be obscurred from view. Unfortunately, such supernova explosions are thought to occur within our galaxy only about once every thirty years. Thus neutrino astronomers may just have to be patient.

From observations made in the x-ray and gamma-ray regimes, it is now known that there are a number of compact objects that are capable of producing extremely high energy particles. For instance, gamma-rays of over 10^9 MeV have been observed from the objects Cygnus X-3, Vela X-1, and LMC X-4. In order to produce such extremely high energy gamma rays, these objects must somehow be capable of accelerating charged particles to even higher energies. One model that has been proposed suggests that a pulsar in these systems accelerates protons to energies of about 10^{11} MeV. These protons strike the atmosphere of a nearby companion star (or gas cloud) and induce reactions which produce pi- and K-mesons. The subsequent decays of the electrically neutral pi-zero mesons give rise to the observed high energy gamma rays. From similar decays of charged pions and kaons, it is therefore expected that these compact objects should also produce extremely high energy neutrinos. The well-known Crab nebula, whose light output is powered by a pulsar located near its center, is shown in Fig. 4. Observations of neutrinos from such objects would test models such as that mentioned above and would help elucidate the nature of these astronomical accelerators.

High energy neutrinos are also produced through the interactions of cosmic rays. The bombardment of the Earth's atmosphere and of the material in the interstellar medium by high energy cosmic rays produces a variety of particles, some of which eventually decay into neutrinos. Measurements of these neutrinos could provide much new information on high energy cosmic ray processes. There should also other astronomical sources of neutrinos. It is generally believed that the observed 3 degree background radiation field is a relic of the Big Bang and that is found everywhere in the universe. Neutrino astronomy may prove to be the only means by which we can test the universality of this radiation. When viewed from the reference frame of a sufficiently high energy cosmic-ray proton, the photons in this radiation field are capable of inducing a pion photoproduction reaction. The subsequent decays of the charged pions will again produce high energy muon- and electron-type neutrinos. Other possible sources of high-energy neutrinos include active galaxies and quasars. Thus it seems clear that neutrinos should be streaming to us from a variety of astronomical sites.

Past and Present Experiments in Neutrino Astronomy

The probability of neutrinos interacting with matter is very small, and grows smaller with decreasing energy. This makes the detection of the low-energy solar neutrinos extremely difficult. Nevertheless, an experiment designed by R. Davis and his collaborators to measure the number of electron-type neutrinos coming to us from the Sun has been underway for about fifteen years. This experiment utilizes the fact that although neutrinos are elusive, they do occasionally interact with matter and do so in very specific ways. In particular, it is possible for a chlorine-37 nucleus to absorb an electron-type neutrino and thereby be transformed into an argon-37 nucleus plus an electron. Low energy muon- and tau-type neutrinos cannot induce this type of reaction. Argon is an inert gas, and as a result can be easily chemically separated from the chlorine. Argon-37 is a radioactive nucleus with a half-life of 35 days, and thus by detecting its subsequent decays one can determine the number of such atoms produced.

Because the probability for a neutrino to induce this reaction is extremely small, the target must contain a very large number of chlorine-37 atoms. In the Davis experiment, the target consists of a tank filled with 100,000 gallons of perchloroethylene - a kind of dry-cleaning fluid. Even with such a large target, the number of argon-37 atoms expected to be produced is still very small - about two atoms per day! Thus it is imperative to reduce as much as possible any other possible sources of argon-37. The major source of such background is produced by cosmic-ray induced reactions. In order to reduce this problem, Davis's target is located in a gold mine approximately one mile underground.

The results of this experiment have produced one of the outstanding problems in current astrophysics. The expected flux of solar neutrinos has been calculated a number of times using sophisticated models of the solar interior and up-to-date knowledge of nuclear reaction rates. While the results of calculations performed by several different research groups agree with one another, they are in serious disagreement with the experimentally determined value. Davis finds only about one third as many neutrinos as the best current models predict. This discrepancy may simply reflect our lack of knowledge of the details of the solar interior, or may indicate that on their way from the Sun to the Earth, neutrinos make transitions from the type to which Davis's experiment is sensitive into one or more of the other types of neutrinos.

The somewhat higher energy neutrinos expected from the gravitational collapse of massive stars have also been searched for. K. Lande and his collaborators have installed a 300-ton water-filled counter surrounding Davis's chlorine solar neutrino detector.

Neutrino interactions in water can produce charged particles that move faster than the speed of light in water. Such particles emit a form of light known as Cerenkov radiation that can be detected by photomultiplier tubes that view the water. At the Artyomovsk Scientific Station in the Soviet Union, a 100-ton scintillation detector has been used to search for anti-neutrinos by using the same reaction as originally employed by Reines and Cowan. These detectors have each been on line for several years, but have so far failed to record any neutrino bursts. The next supernova in our galaxy may occur tomorrow, so these detectors could soon provide exciting results.

The high energy muon-type neutrinos produced by cosmic-ray interactions in the Earth's atmosphere have been observed in several experiments. These neutrinos, whose energies are greater than or equal to about 1000 MeV, are detected by observing the secondary muons they produce in reactions in or near the detector. Because the chance of such reactions occurring is so small, the expected flux of these neutrino-induced muons is negligible compared to that of the muons produced directly by cosmic ray interactions in the atmosphere. Thus such experiments must be conducted deep underground (or underwater) where the flux of atmospheric muons is greatly attenuated, but the flux of neutrinos is scarcely different from that at the surface. As can be seen in Fig. 5, at a depth of about 3 kilometers, the flux of atmospheric muons is reduced by 10 orders of magnitude from that observed at the surface. Nevertheless, even at this depth the neutrino-induced muon flux is still smaller than the vertical flux of atmospheric muons. However, by looking at large zenith angles (i.e. toward the horizontal direction) one increases the effective depth of the detector. The reason for this is that in order to reach a detector 3 kilometers underground, a cosmic ray arriving from a direction 30 degrees above the horizontal must have traversed 6 kilometers of rock. Thus such a technique provides an increased sensitivity to the neutrino-induced muon flux.

In 1965, two separate groups reported the first observations of atmospheric neutrinos. A collaboration led by F. Reines and M.Crouch between the Case Institute of Technology and the University of Witwatersrand operated a large-area liquid scintillator detector 2 miles underground in a South African gold mine. In a period of two years they observed 35 near horizontal events that could be attributed to neutrino interactions. A collaboration between the Tata Institute, Osaka City University, and the University of Durham performed a similar experiment at a depth of about 1.4 miles in the Kolar Gold Fields in India. They observed fewer events than did the South African experiment, but were able to measure the arrival direction of the muons. Although the total number of events was small, some upward-moving muons were observed - a unique signature of neutrino-induced events.

Continued experiments in South Africa, India, and subsequent experiments by a group from the University of Utah and by the Baksan Neutrino Observatory in the Soviet Union have now extended the measurements of the cosmic- ray muon flux to an effective depth of about 80 kilometers. The results of these remarkable experiments are summarized in Fig. 5. Below a depth of about five kilometers, an essentially constant flux of muons is observed. The only particle able to traverse such large amounts of rock without attenuation is the neutrino. Thus the identification of these muons as being due to neutrino interactions is well established.

The flux of neutrinos inferred from these underground measurements is consistent with that expected from neutrino production by cosmic ray interactions in the Earth's atmosphere. Thus to date, there has not been a definitive observation of extraterrestrial high-energy neutrinos. However, a number of present and planned experiments are designed to search for these particles. A novel scheme presently being employed by J. Elbert and his colleagues at the University of Utah involves the use of a large above-ground array of mirrors and photomultiplier tubes known as the Fly's Eye. Like the compound eyes of certain insects, each of this detector's 880 separate elements views a distinct region of the sky. A portion of this system is shown in Fig. 6. This observatory utilizes the fact that extremely high energy cosmic rays (including neutrinos) can interact with matter in the Earth's atmosphere in such ways as to produce Cerenkov and scintillation light. For cosmic rays with energies on the order of 10^{14} MeV, this light can be seen (on clear moonless nights) by the the Fly's Eye from a cylindrical volume roughly 20 kilometers in radius and 20 kilometers high. By recording the time at which each sensor detects light, the path of the cosmic ray particle through the atmosphere can be reconstructed. Again, a unique signature of neutrino-induced reactions would be trajectories that originate in the Earth and travel upwards. Searches of this kind have to date not provided any evidence of such neutrinos, but the hunt goes on.

Future Prospects

Because of the continuing discrepancy between the theoretical and experimental results for Davis's chlorine detector, a number of new solar neutrino experiments have been proposed. The one which has been studied most extensively is a radiochemical experiment which uses gallium-71 as a target. This system would be more sensitive to the abundant low-energy solar neutrinos than the chlorine detector, and would allow us to determine if neutrinos do change from one type to another during their eight minute flight to us from the Sun. However, in order to record one neutrino capture per day, 50 tons of gallium are required. The price of this amount of gallium is about 25 million dollars, and funding for this important experiment is currently being sought. Other schemes to detect solar neutrinos using lithium-7, bromine-81, technetium-99, and indium-115 targets are also being investigated. Clearly further experiments are needed to resolve this intriguinq problem.

Throughout the world there are now a number of deep underground laboratories in which experiments are currently being performed to search for the decay of the proton. Like neutrino experiments, they must be done underground in order to reduce the cosmic ray backqround. These experiments use detector sytstems which are also sensitive to neutrino interactions and several of these experiments have begun to record high energy neutrino interactions. Further running times should provide a wealth of new information on the flux of such neutrinos.

Another ambitious project to study very high energy cosmic ray muon and neutrino interactions is now underway. The DUMAND (Deep Underwater Muon and Neutrino Detector) system would enclose a volume of 3.5×10^7 cubic meters of ocean water. An array of 756 photomultiplier tubes arranged in 36 separate strings of 21 tubes each would be used to detect the Cerenkov radiation produced in high energy muon and neutrino interactions with the water. Along each string, photomultiplier tubes would be spaced every 25 meters, and neighboring strings would be 50 meters apart. In Fig. 7, a prototype of one such string is shown being prepared for testing in the ocean. This detector, which is now in the development stage, would be located at a depth of about 4.8 kilometers in the Pacific Ocean just off the coast of Hawaii. With this huge "all-sky camera", high energy neutrinos from cosmic ray interactions and from discrete sources such as those discussed above should be observable.

Neutrino astronomy is thus still in its infancy, but has already provided some surprises. A number of huge neutrino "telescopes" are now on the air, and still larger ones are being developed to detect these elusive particles. As with any new type of astronomy, it is impossible to predict all of the things we may eventually see through this new window on the universe.

Figure Captions

1. Spectrum of electrons observed from the decays of free neutrons (after J. M. Robson, Phys. Rev. 83 , 349 (1951)). The fact that one observes a continuous spectrum of electron energies up to the maximum allowed by energy conservation led W. Pauli to suggest that another particle must also be emitted in the process of beta decay. This object is now known as the neutrino.

2. A high energy neutrino-induced reaction as recorded in the 15-foot bubble chamber at Fermilab (courtesy of D. Chapman and J. Lys). A neutrino (which left no track) entered the chamber from the left, and near the center of the picture it struck the nucleus of a target neon atom. The reaction produced a shower of charged particles (protons, pions, and electrons) which formed the 17 tracks that are seen to originate from the reaction vertex.

3. Two views of the galaxy NGC 7331, before and during the maximum of the supernova of 1959 (courtesy Lick Observatory). Such an event is believed to be the result of the gravitational collapse of the core of a massive star and may be the source of a brief but intense burst of neutrinos.

4. The Crab Nebula (courtesy Lick Observatory). Pulsars such as the one which powers the Crab Nebula can accelerate charged particles to extremely high energies. The subsequent interactions of these particles may produce very high energy neutrinos.

5. The observed vertical flux of cosmic ray particles (muons) as a function of effective depth below ground (after M. Crouch, Proc. of the Workshop on Science Underground,

AIP Conf. Proc. 96, (1983) p. 225). The constant flux observed below a depth of about five kilometers is due to atmospheric neutrino interactions in the detector or surrounding rock walls.

6. A portion of the University of Utah's Fly's Eye observatory (courtesy J. Elbert). This system consists of 67 62-inch mirrors with 12 or 14 photomultiplier tubes mounted in the focal plane of each mirror. The detector is designed to observe ultra-high energy cosmic rays via the scintillation and Cerenkov light produced by their interactions in the Earth's atmosphere.

7. A prototype for the DUMAND array consisting of a string of 5 photomultiplier tubes in their glass pressure vessels is prepared for lowering into the Pacific Ocean off the coast of Hawaii (courtesy J. Learned). In the full-scale DUMAND project, 36 strings each with 21 photomultiplier tubes will be located at a depth of about 4.8 km. The system is designed to record the interactions of high energy muons and neutrinos with the ocean water.

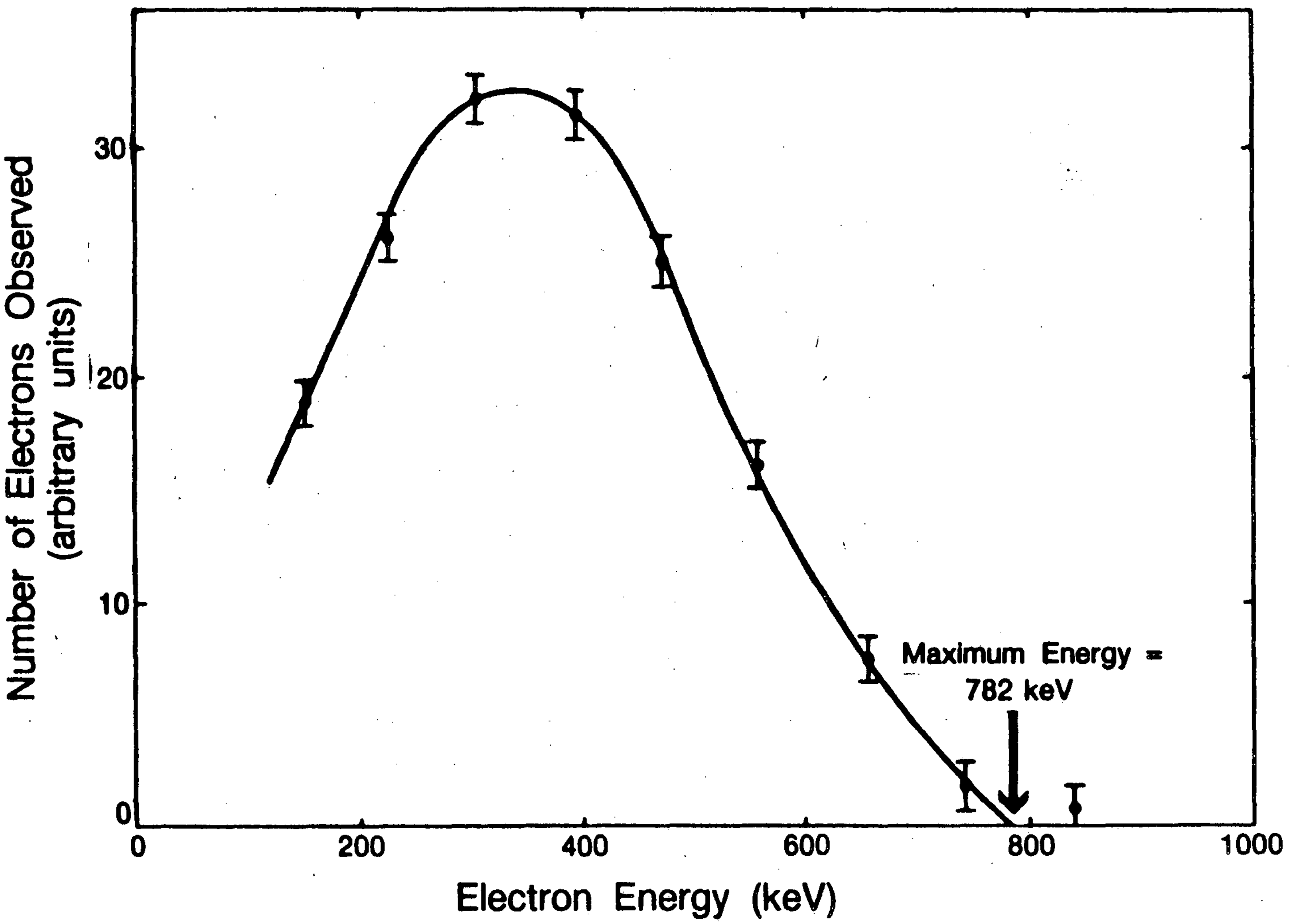

Number of Electrons Observed
(arbitrary units)
30
20
10
0
0
200
400
600
800
1000
Electron Energy (keV)
Maximum Energy =
782 keV

Fig. 1

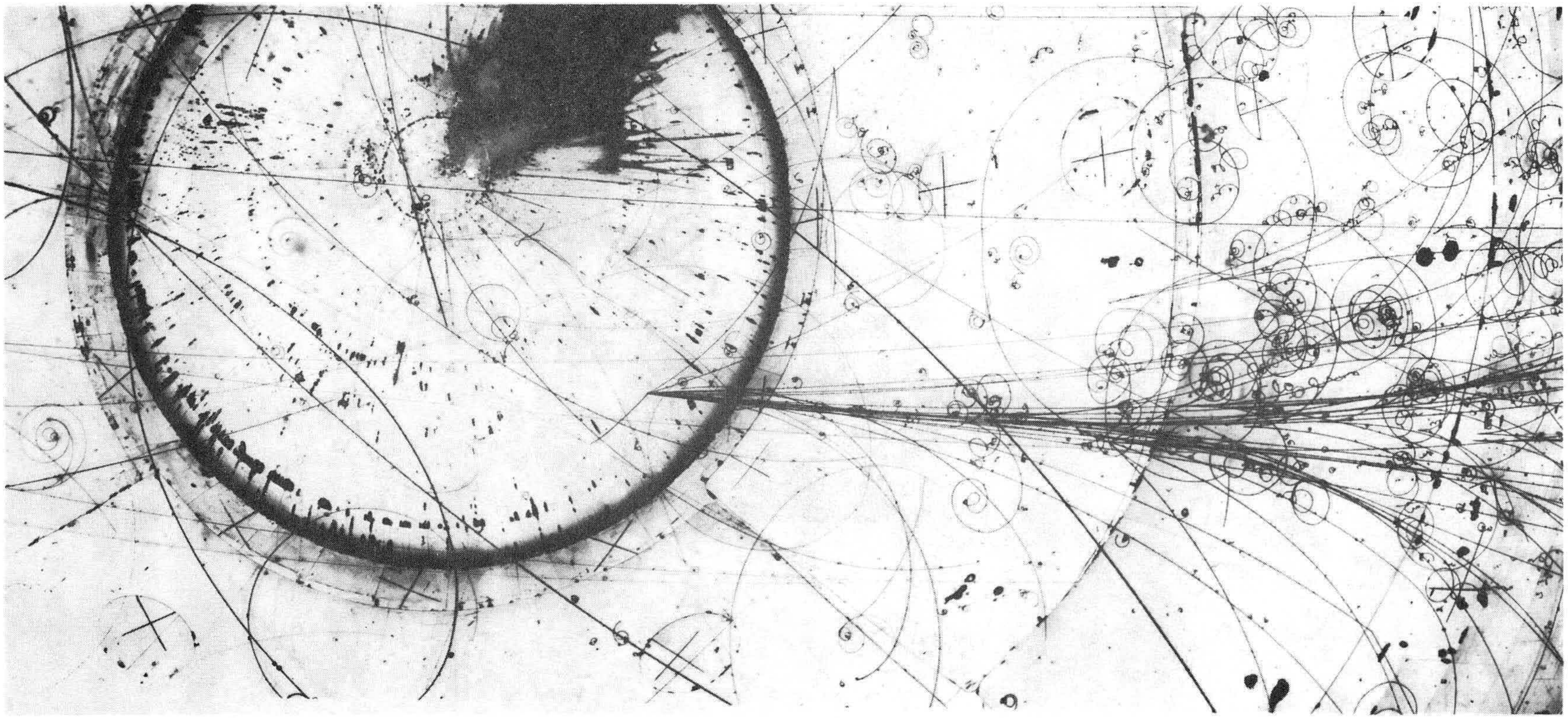
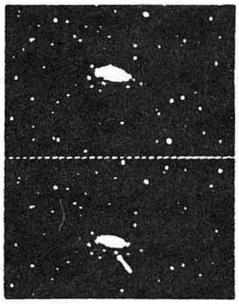


Fig. 2



S17 Two views of NGC 7331, before and during maximum of supernova of 1959 (Crossley reflector).

Fig. 3

N5 Crab Nebula in Taurus (Messier 1, NGC 1952) in red light.

Fig. 4

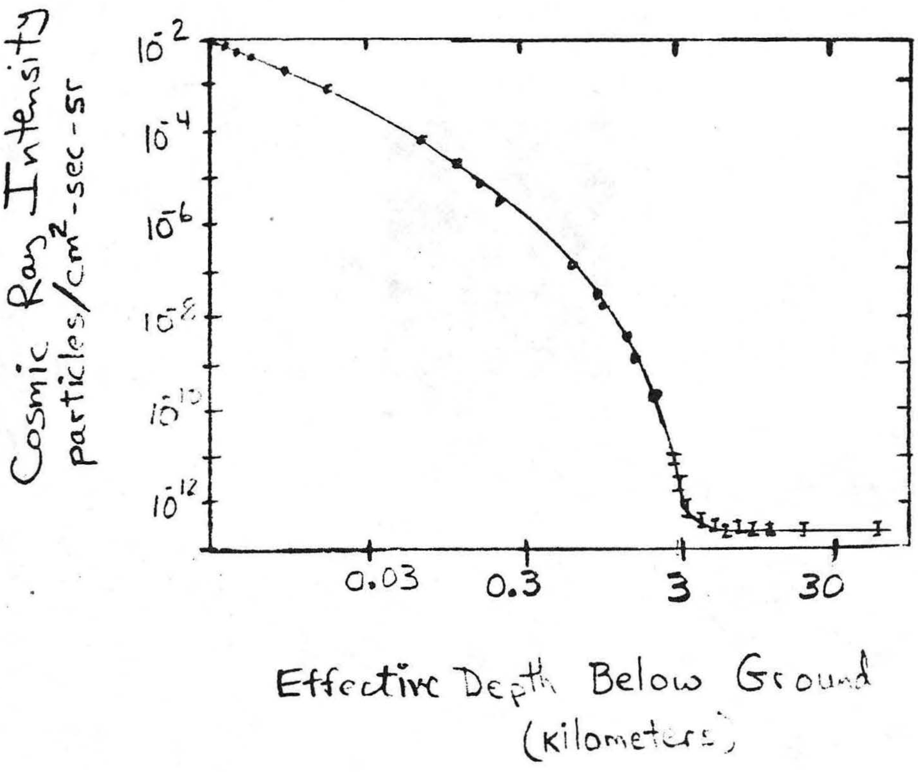

Cosmic Ray Intensity
particles/cm²-sec-sr
10⁻²
10⁻⁴
10⁻⁶
10⁻⁸
10⁻¹⁰
10⁻¹²
0.03
0.3
3
30
Effective Depth Below Ground
(kilometers)

Fig. 5

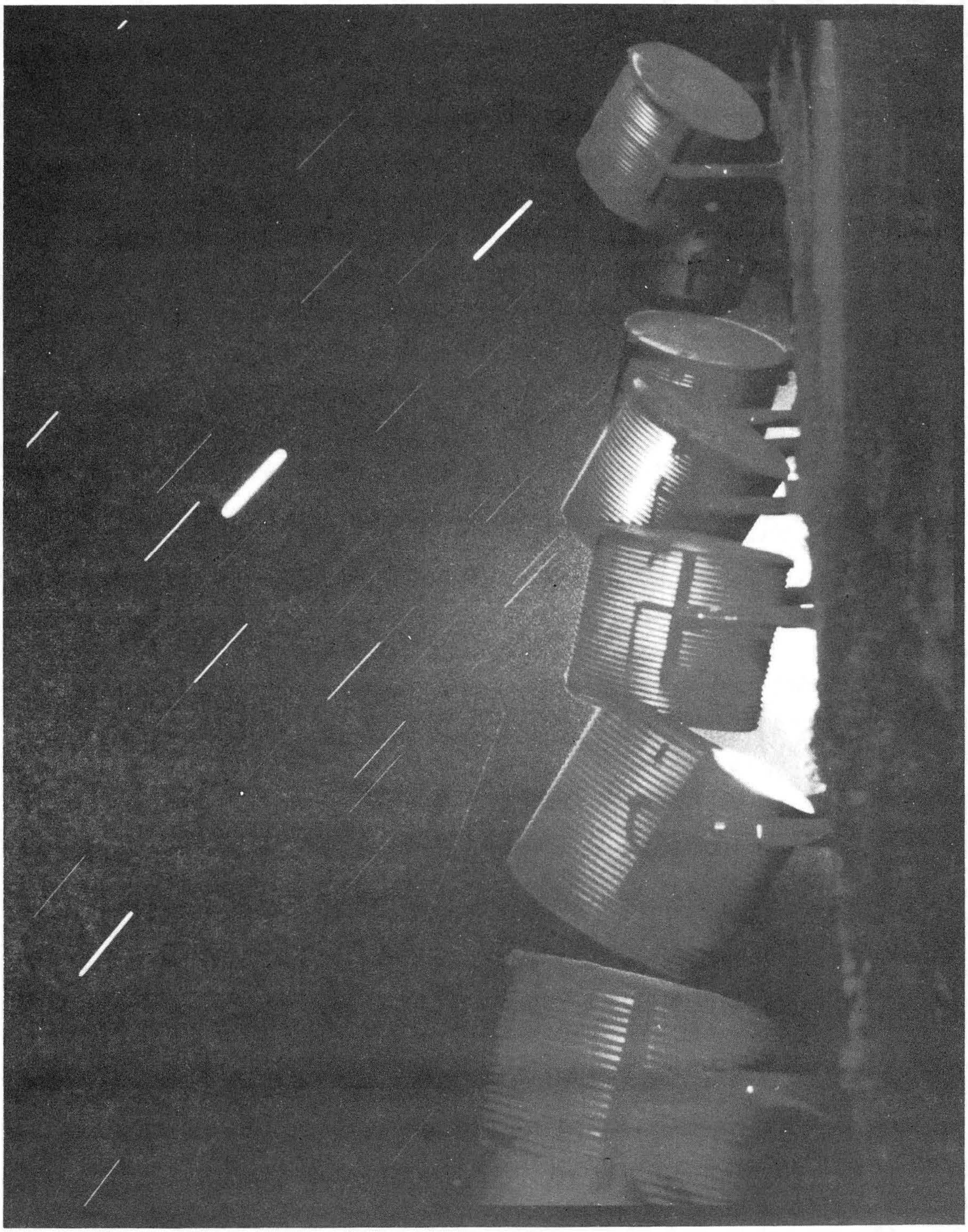


Fig. 6

CBB 840-9280

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