Gamma Rays and Neutrinos as Clues to the Origin of High Energy Cosmic Rays

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Compact regions in the Milky Way, such as accreting degenerate binary stars, may be sites of acceleration of particles with energies far greater than produced at any man-made accelerator, present or proposed. If so, they would emit characteristic neutral radiation of ultra-high energy, which might be strong enough to be detectable at Earth. The quest for these faint but energetic signals is the focus of more than 50 large, ground-based experiments that are looking for high energy photons or neutrinos from point sources in our galaxy and beyond. Several sources have been claimed, but the signals appear to have unexpected and puzzling features that must be clarified before the field can settle into a routine phase of systematic investigation. In the meantime, the potentially profound implications for particle physics, as well as astrophysics, make this field one of intense activity.

CHARGED PARTICLES (SUCH AS PROTONS, IONIZED ATOMIC nuclei, and electrons) injected from cosmic accelerators follow complicated paths through the turbulent magnetized plasma of the interstellar medium. These charged "cosmic rays" therefore arrive at Earth from all directions. Their local trajectories bear little or no relation to their sources, so it is not possible by detecting the cosmic rays themselves to identify their sources. There is a way to beat this problem, however. Whenever high energy particles interact with matter, photons and neutrinos are produced. Because they are electrically neutral, these particles travel in straight lines. Therefore, any neutral particle detected at Earth is on a trajectory directed from its point of origin to the observer. If the source regions are compact, and if there is enough target material nearby, then one has the makings of a point source of photons or neutrinos. (Of course, if all the accelerated charged particles interact and get absorbed in the region of a source, then it does not contribute to the pool of galactic cosmic rays. Such a completely absorbing accelerator would still be extremely interesting, however.)

The discovery of several (*1*) apparently prolific point sources of photons with energies in the range of 1 TeV (approximately 1.6 erg per photon) and higher has led to the intense experimental activity in this field. The map (Fig. 1) shows the locations of some 50 large ground-based detectors in operation or under construction. One potential implication is that the ultra-high energy cosmic rays may be accelerated in energetic, compact sources rather than in more extended regions such as expanding supernova blast waves, a favored site for the origin of the bulk of the cosmic radiation at lower energy. Conclusions such as this may be premature, however, because there are some indications that the detected "photons" do not behave like real, electromagnetic photons, but rather have some characteristics of hadrons. Hadrons, such as protons, neutrons, and pions, are particles that interact through the strong force and produce large numbers of secondary hadrons when they interact. Photons couple to hadrons through the electromagnetic force, however, and they should therefore seldom produce hadrons when they interact at the detector. Thus, when the signals show the earmarks of prolific hadron production, the experimental results must come under close scrutiny.

There are three possibilities: (i) Photons become more hadron-like at high energy; (ii) the signals are not photons, but some new neutral hadron; or (iii) the signals are really just unfortunate fluctuations. There is some theoretical justification (*2*) for the first item, but it is difficult to make the photon become sufficiently hadronic at low enough energy. Many exotic possibilities for new particles have been discussed (*3*), but many have also been ruled out after reflection. The third possibility has serious advocates (*4*), but is difficult to maintain in the face of many independent and sometimes reinforcing observations.

Gamma Ray Astronomy

Studies of gamma rays with energies in the 50- to 5000-MeV range have been used to map regions of cosmic ray interactions with the gas in the interstellar medium. The photons (γ) are produced through reactions like

$$p + \text{gas} \rightarrow \pi^0 + \text{other particles} \quad (1)$$

followed immediately by the decay of the neutral pion ($\pi^0 \rightarrow 2\gamma$). Beautiful and detailed maps clearly showing the galactic plane as well as the galactic center region and a few point sources have been made with data obtained by the SAS-2 and COS-B satellites (*5*). This kind of investigation will be continued in coming years with higher sensitivity by the high energy gamma ray experiment on the orbiting Gamma Ray Observatory (GRO) (*6*) and also by a French-Soviet experiment on the Gamma-1 satellite. Experiments of this type originated in the late fifties and sixties with work by the M.I.T. group (*7*) who sent detectors aloft on balloons and satellites.

The vast majority of the cosmic rays have energies from 1 to 50 GeV per nucleon. It is these particles that are the progenitors of the relatively low energy gamma rays mapped in the satellite experiments. The source function for the photons is a convolution of the

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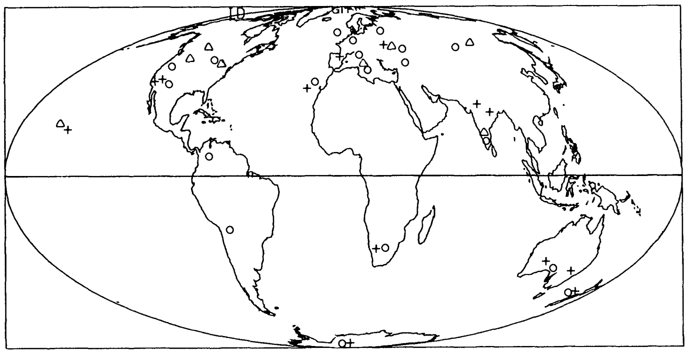

Fig. 1. Map showing locations of air shower (○), atmospheric Cherenkov (+), and large underground (△) experiments.

cosmic ray flux with the density, ρ, of gas in the interstellar medium. The number of photons produced per unit volume per unit time at position **r** is

$$q_\gamma(E, \mathbf{r}) = 4\pi \int \phi(E', \mathbf{r})\rho(\mathbf{r}) \frac{d\sigma(E, E')}{dE} dE' \qquad (2)$$

where $\phi(E, \mathbf{r})$ is the flux of cosmic ray nucleons. The differential cross section, $d\sigma(E, E')dE$, when multiplied by the flux of cosmic ray nucleons, gives the number of secondaries with energies between E and $E + dE$. The factor 4π accounts for the fact that the flux is defined per unit solid angle. When numbers are inserted into this equation, it turns out that, even from the galactic center, which is the most intense site of cosmic ray activity, the ratio of photons to the cosmic rays that produce them is

$$\phi_\gamma/\phi_p < 10^{-4} \qquad (3)$$

The small value of this ratio is primarily a consequence of the fact that the photons travel straight out of the galaxy, and so have only one chance to be observed, whereas protons and other charged particles may cross the galactic plane thousands of times before wandering off into the galactic halo or intergalactic space.

Since the cosmic ray flux falls quickly with increasing energy, the intensity of photons rapidly falls below the threshold of detectors of a size that can be carried aloft on balloons or satellites. At 100 TeV, for example, the cosmic ray flux itself is of order 3×10^{-9} particles per cm^2 s^{-1} sr^{-1}. A photon flux four orders of magnitude less than this would give only three events per hectare per day. Coping with such low intensities requires detectors of very large effective area that can be exposed for long periods of time. This is only possible at present with ground-based detectors.

Air Showers

A detector on the ground—even one on a high mountain—cannot see a primary particle directly, but only the cascade of secondaries its interaction generates in the atmosphere. Each shower consists of a pancake-like group of ultrarelativistic particles that multiplies from the single incident, "primary" particle, or photon (Fig. 2). There are different ways to detect such air showers, depending on the energy range (*1*). For primary photons or nuclei with energies of order 100 TeV or higher, an array of detectors on the ground can detect the shower front and, by fast timing, reconstruct the direction of the shower and its primary. Figure 3 shows an example of an air shower array (*8*). In the TeV range, the particles in the shower (mostly electrons and positrons generated in electromagnetic subshowers) have died out before ground level, but the atmospheric Cherenkov light generated by the particles near shower maximum high in the atmosphere can be detected in an appropriate telescope.

There are major practical differences between the two types of experiment. The Cherenkov telescope can operate only on clear, dark nights, when the faint light produced high in the atmosphere can be detected by sensitive phototubes viewing mirrors pointed at the source. An air shower array is sensitive only to particles of much higher energy, where the flux is lower, but it can be operated day and night in all weather. The South Pole Air Shower Experiment (SPASE) (*9*), which has operated with high duty factor through two Antarctic winters (Fig. 4), testifies to the simplicity and dependability of the classic air shower array. In addition to operating almost continuously, an air shower array accepts showers from all directions at once, provided they are not too far from the vertical.

Because showers generated by photons from cosmic sources look very much like showers generated by ordinary cosmic ray nuclei, some kind of "tag" is needed to discriminate a signal from the isotropic background of cosmic ray showers. Usually, one simply looks for a significant excess of events from the direction of the source, as in the original proposal by Cocconi (*10*). If a potential source has a characteristic periodicity established independently, this can be used as a tag. Examples might be the orbital period of a binary star observed with x-ray detectors or a pulsar period determined by a radio telescope. Neither of these tags makes a positive identification of the signal as photons. Because signals are often weak and sometimes of marginal statistical significance, a great deal of effort is being devoted to building experiments that can discriminate photons from cosmic ray nuclei on a shower-by-shower basis.

One of the principal techniques for making this distinction was introduced long ago, when the first experiments were designed to look for point sources at ultra-high energy. The idea is based on the fact that photon showers are expected to be predominantly electro-

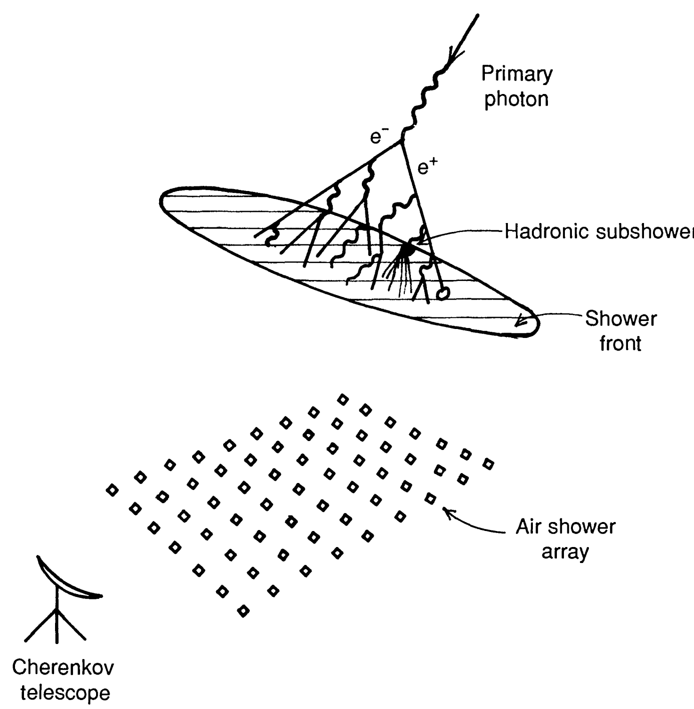

Fig. 2. This sketch shows an air shower generated by a primary photon of energy ~50 TeV or higher as it approaches an air shower array. This example includes a single hadronic subshower in which a photon produces pions, some of which decay to muons. The muons can penetrate to trigger shielded detectors. A Cherenkov telescope can detect signals from showers of lower energy (~1 TeV) in which the particles are absorbed before they reach the level of the detector.

magnetic. A photon shower develops by alternate pair production and bremsstrahlung, as indicated in Fig. 2. Occasionally (relative probability 0.3%) a photon in the cascade interacts hadronically instead of electromagnetically. When that occurs, charged pions are among the products, and they can decay to give muons. Other sources of muons in electromagnetic cascades are still more rare. In a cascade induced by a cosmic ray nucleus, on the contrary, production of pions is the dominant feature. Thus muons are expected to be much less abundant in photon showers than in cosmic ray showers (by about a factor of 30 for ~GeV muons after accounting for the multiplication of photons in a shower).

A collaboration of scientists from the United States, Japan, and Bolivia (*11*) used this idea as the basis of an attempt to map the galaxy with cosmic photons of ultra-high energy (that is, energetic enough to make observable air showers). They built a 60-m^2 shielded counter at the center of an air shower array on Mount Chacaltaya in Bolivia (5200 m above sea level). The shielding was designed to be thick enough to absorb virtually all the electrons, positrons, and photons in the shower front and to detect the penetrating component, mostly muons with energy $E_\mu > 700$ MeV. To enhance the sensitivity to a signal, they selected "muon-poor" showers. Although there was a slight indication of an excess of events with low muon content, these events were not correlated with galactic structure. The result was a limit, $\phi_\gamma/\phi_N \leq 3 \times 10^{-4}$, still above the maximum ratio expected. Results from a preliminary version of the Chicago-Michigan-Utah air shower experiments (*12*) have already reached the level of the Chacaltaya experiment. Reaching the level of sensitivity of one photon shower in 10^5 cosmic ray showers, in order to see the galactic disk mapped in 100-TeV photons, is a challenging goal. If achieved, it would offer a well-understood, steady calibration source. Searches for accreting binaries and other high energy sources need some sort of "standard candle" because they appear to be highly variable in intensity and sporadic.

Point Sources

Early attempts to look for air showers generated by high energy photons from point sources were made in England by Jelley and Galbraith (*13*) and in the U.S.S.R. by Chudakov and Zatsepin (*14*). They initiated and developed the technique of using mirrors pointed at the source (or drifting across the source as Earth turns) to record flashes of Cherenkov light (*15*) from the showers. One of the early applications was a search for TeV photons from the Crab Nebula. The negative result had an important implication (*16*). Synchrotron emission from the Crab Nebula was known to imply the existence of ultrarelativistic electrons as its source. Before these observations, a leading candidate for the electrons was thought to be (*10*) acceleration of protons followed by

$$p + \text{gas} \rightarrow \pi^{\pm} \rightarrow \mu^{\pm} \rightarrow e^{\pm} \quad (4)$$

Protons (unlike electrons) could have been accelerated in the initial explosion and survived to the present to generate the electrons. For this to be the case there would have to be a flux of ~TeV photons from

$$p + \text{gas} \rightarrow \pi^0 \rightarrow 2\gamma \quad (5)$$

two orders of magnitude greater than the upper limit that was observed. The conclusion therefore was that the electrons have to be directly accelerated. Subsequently the Crab pulsar was discovered, and we now know that the electrons are continuously energized, ultimately by the rotational energy of the strongly magnetized, rapidly spinning neutron star at the center of the Nebula.

Fig. 3. Photograph of a portion of the Chicago air shower array at Dugway, Utah (courtesy of J. Cronin).

It is only recently (*17*) that ~TeV photons from the Crab Nebula have finally been measured with high statistical precision by means of the atmospheric Cherenkov technique with a large, imaging telescope. This was accomplished by the Whipple group with the help of a criterion they developed to discriminate between photon- and hadron-initiated showers. Using simulations of images of the Cherenkov light pool as seen with their telescope, the group has shown that the light pool of proton showers is more irregular than that of photon showers. When they apply the criterion based on this observation to the Crab Nebula, the significance of the signal increases to 9σ. The relatively low intensity of the photon signal they observe is consistent with the "inverse-self-Compton" picture (*18*) in which the synchrotron photons in the Nebula are kicked up to high energy by inverse Compton scattering from one of the high energy electrons before it loses its energy to synchrotron radiation.

The first point source to be detected with the air Cherenkov technique was Cygnus X-3 in 1972 by a Soviet group at the Crimean Astrophysical Observatory (*19*). The star had just gone through a period of intense activity during which it was the brightest pointlike radio source in the sky. Cygnus X-3 is thought to be a low mass x-ray binary comprising a neutron star in orbit with a companion of mass less than the Sun. Observations with x-ray detectors on satellites show a characteristic 4.8-hour periodicity, most likely the orbital period of the binary system. This periodicity

Fig. 4. Photograph of the South Pole Air Shower Array. The building in the foreground is the clean air facility, unrelated to SPASE (courtesy of J. Perrett).

was seen in the first air Cherenkov detection. Cygnus X-3 may be powered by accretion from the companion star onto the neutron star, but it is hard to be certain just what the system is because it lies in the galactic plane, about 30,000 light-years away, and is not visible in optical wavelengths through the intervening dust.

Since then, a few other x-ray binary stars have been detected with air Cherenkov telescopes and air shower arrays (*20*). These include Hercules X-1 and Vela X-1, both of which have companion stars visible in the optical wavelength range. Parameters such as mass, separation and so forth are therefore much better known than for Cygnus X-3. The sources are not always visible above background, however. In fact, this is a key feature of the observations, which suggests that the sources may undergo flaring or other outbursts of intense activity during which they are powerful enough to be visible at Earth.

Cygnus X-3

Cygnus X-3 is perhaps the most intensely studied source in the ~TeV and >100 TeV energy bands. The report (*21*) that it had been seen by an air shower experiment at sea level, sensitive only to events with energy greater than 2000 TeV, caused great excitement—including a headline on page 1 of the *New York Times* (*22*), "Mystery of Cosmic Ray Origin May Be Solved." It is generally believed that photons with energies this high could not be generated by radiative processes involving electrons because of the severe synchrotron losses that such electrons would suffer. Instead, the photons would have to come from decay of neutral pions produced by collisions of accelerated protons and heavier ions. During a 4-year period from 1976 to 1980, some 15 excess events (over a background of 15 in the relevant angular bin) had been accumulated. In addition, the events in the angular bin corresponding to Cygnus X-3 showed its characteristic 4.8-hour periodicity. The result was soon confirmed by the Haverah Park (Leeds, United Kingdom) experiment (*23*), though with a signal-to-background ratio that required using the known 4.8-hour periodicity to bring the signal above the background.

Given the distance to Cygnus X-3 and the high energy per particle, Hillas estimated (*24*) that this single source could supply all the galactic cosmic rays with energies greater than 1000 TeV. At the same time, such a single powerful source is problematic. The implied luminosity of the source (10^{39} erg s^{-1}) is greater than the generally accepted upper limit for a source powered by accretion onto a neutron star. With this much power, a compact system could destroy itself on a time scale short by astronomical standards (*25*).

Subsequent observations of Cygnus X-3 have produced mixed results. One of the most tantalizing is the report of a 12.6-ms periodicity that could be the signal of a fast pulsar in the system (*26*). During one of its characteristic outbursts in the radio-frequency range in 1985, excess air showers were reported by several experiments, including Baksan (*16*) in the Soviet Union and Haverah Park in Britain (*27*). Other observations since 1985 have generally seen significantly smaller signals (*28*) or set upper limits (*12, 28*) as much as a factor of ten lower than implied by the early results (*22, 23*). The possibility of an association of air shower signals with the intense radio outbursts of Cygnus X-3 is an interesting one. Since 1985 no intense bursts occurred until the past summer, when there were two bursts, one on 2 June and another on 21 July 1989 (*29*). Several air shower groups are actively looking to see whether ultra-high energy radiation is associated with these radio outbursts.

The most remarkable recent news on Cygnus X-3 is the report (*30*) from the Fly's Eye of ~10^{18}-eV showers from the direction of Cygnus X-3. The Haverah Park group looked at their data in an overlapping time period and found (*31*) an upper limit for a signal in its energy range about five times lower than the Fly's Eye result. It has been noted that the techniques are different, but it is not yet clear whether this could cause the apparent conflict between the two results. A novel feature of a signal of this energy is that neutrons of 10^{18} eV have a decay length about equal to the distance to Cygnus X-3 (*32*). Chipping neutrons off nuclei at the source would be the most energy-efficient way to produce the signal.

The Muon Problem

A worrisome aspect of the first air shower detection of Cygnus X-3 was the fact that the signal events appeared to have nearly as many muons as the background (*33*). The Kiel air shower array (*22, 33*) had a rudimentary muon detector consisting of 367,500 spherical flash tubes shielded by 32 radiation lengths of concrete under the center of the array. This is deep enough so that electromagnetic cascades will be absorbed, but muons with energy above about 1.6 GeV can penetrate to the underground detector. Ironically, the first experiment designed to solve the muon problem by improving the power to discriminate against hadronic background (*28*) found signals from Her X-1 (*34*) at least as puzzling as the Kiel data on Cygnus X-3. Of 11 signal events from Her X-1, all but 3 had more muons than would be expected for ordinary cosmic ray background showers of comparable size and direction.

It has been suggested (*2*) that the photoproduction cross section may rise more rapidly than a simple logarithmic extrapolation of accelerator measurements, as a consequence of a threshold above which the gluon content of the photon begins to dominate the interactions of photons with hadrons. This would mean that photons look more like hadrons when they interact at high energy. It appears difficult in the framework of such a model to make the hadronic cross section of the photon big enough to account fully for the observations. Experiments at the electron-proton collider in Hamburg will soon give some direct information about photoproduction at very high energy.

Another topic relevant to the muon problem is the image analysis of ~TeV showers used by the Whipple group to isolate photon-induced showers and enhance the signal-to-background ratio from

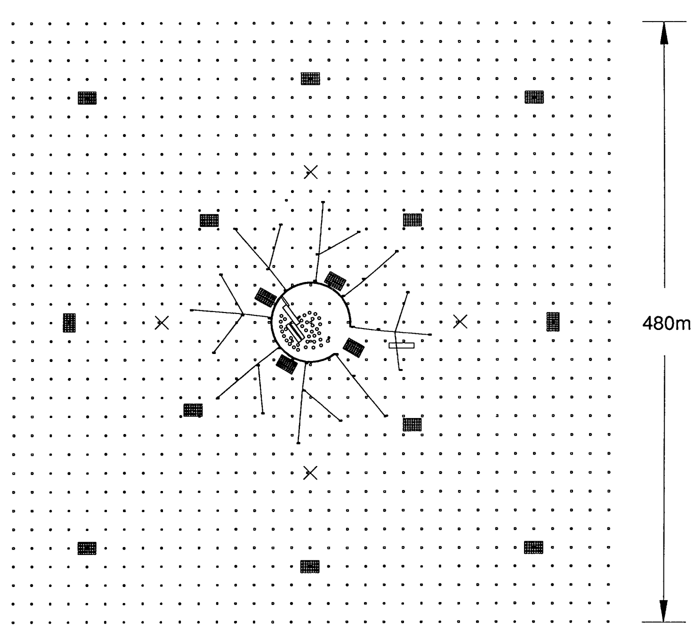

Fig. 5. Diagram of the air shower complex at Dugway, Utah.

the Crab Nebula (*17*). When they apply this criterion to their observations of Her X-1, however, the $\sim 3\sigma$ signal disappears (*35*). At the relatively low energies of the air Cherenkov experiments, a hadronic photon is definitely out of the question. Nevertheless, it is hard to dismiss the events from the direction of Her X-1 as a statistical accident because at least three independent experiments (*34, 36, 37*) have reported seeing this source during the summer of 1986 with a periodicity slightly shifted from the x-ray pulsar period. Moreover, it is possible to build reasonable physical models to account for the slightly shifted period (*38*).

An even more puzzling development occurred in early 1985 when two deep underground experiments (requiring muons with ~TeV or higher to penetrate from the surface) independently reported signals from Cygnus X-3 with its characteristic 4.8-hour period (*39*). The data had been accumulated over a period of several years, overlapping with the air shower observations. Partially overlapping, but somewhat later data runs from two larger deep underground detectors (Kamioka and Frejus) fail to show any signal (*40*). New detectors of large area, particularly the MACRO (Monopole, Astrophysics, and Cosmic Ray Observatory) experiment at Gran Sasso and Soudan 2, will investigate this puzzle with high sensitivity.

Some Air Shower Experiments

The large air shower complex (*8*) under construction at Dugway Proving Ground in Utah was specifically designed to provide good coverage for low energy muons in air showers. The muon detectors, built by a group from University of Michigan, are buried under 10 feet of earth, giving a muon threshold of approximately 1.3 GeV. They will have a total sensitive area of 2560 m^2, distributed in 16 detectors, as shown in Fig. 5. Eight of these muon detectors have been operating in coincidence with a small surface array of 33 stations built by a University of Utah group.

The full configuration of detectors at this site will include a large surface array of 1089 stations. The total area inside its perimeter will be 2.3×10^5 m^2. This array, which is being built by a group from the University of Chicago, has a subset of its detectors running now and is scheduled for full operation beginning in 1991. A novel feature of the array, designed to give the best possible timing and hence to optimize the angular resolution, is that it works with a local trigger. Each station is connected by fast timing cables only to its nearest neighbors. Time differences with neighboring stations and pulse heights are stored locally by a microprocessor, and data is read out periodically over a local area network (Ethernet). This scheme removes some of the problems of timing calibration that arise in a conventional array in which the fast timing pulses from each detector are sent to a central counting house over cables of various lengths.

In addition to the construction at Dugway, the Cygnus array at Los Alamos National Laboratory is being extended to cover 7×10^4 m^2. This experiment is a collaboration of groups from University of Maryland, University of California at Irvine, Los Alamos, and George Mason University. The group is also extending the coverage for muons by drilling holes to insert auxiliary muon detectors 20 m into a bluff below a portion of the surface array (Fig. 6). The primary muon detector, which allows rudimentary visualization of muon tracks, will continue to be the shielded detector for the Los Alamos neutrino experiment E-225.

An experiment that addresses other aspects of ultra-high energy gamma ray astronomy is the Bartol-Leeds experiment, SPASE. Hillas had suggested (*41*) that an air shower array be deployed at South Pole. The advantages that make up for the difficulties of working there are several. Most importantly, any source that is in the field of view is always visible and always at the same elevation. At South Pole there is no chance that a source will be below the viewing horizon when it is active. Moreover, the background will not vary as the source rises and sets. In addition the site is at a high altitude, which allows a relatively low threshold and high counting rate. At present, this relatively small array has no capability for separately detecting the muon component.

An added bonus for SPASE was Supernova 1987A, which occurred after the proposal for the experiment had been accepted. Unfortunately, as discussed next, this supernova does not appear to be a strong enough source of high energy photons so far to have been visible in this or any other air shower array in the Southern Hemisphere.

Supernova 1987A

A new type-II supernova is likely to be a cosmic accelerator (*42*). If particles are accelerated inside the supernova, associated production of photons and neutrinos could be expected to occur as long as the ejected envelope is sufficiently dense. Apart from a 3.9σ excess of TeV gamma rays for two nights in January 1988 (*43*), however, only upper limits on energetic photon signals from this supernova have been published. In terms of the total power, L_p, in accelerated particles at the source needed to produce a photon signal at Earth, the best current limit in the air shower range is (*44*) $L_p < 2 \times 10^{39}$ erg/s. The limit from the Japan–Australia–New Zealand (JANZOS) air Cherenkov experiment (*43*) corresponds to $L_p < 5 \times 10^{38}$ erg/s. For comparison, the implied power of the 14–15 January 1988 signal was 2×10^{39} erg s^{-1}.

A scenario proposed by Woosley and Chevalier (*45*) to account for a possible submillisecond optical pulsar (*46*) could imply that the supernova would brighten considerably in high energy particles in the near future. This could occur if a highly magnetized, rapidly rotating neutron star has been smothered by matter falling back from the inside of the shell which is gradually being accommodated by the pulsar (*45*). Secondary particle production could occur for several more years if a beam turns on. Another possibility is that the January 1988 event was an isolated flare of a kind that could occur after particles had been accelerated and accumulated for some time and then dumped (by turbulence) into a dense target region (*47*).

Neutrino Astronomy

Neutrino astronomy is complementary to gamma ray astronomy because it will give a different kind of information about cosmic accelerators. In some ways, the motivation for high energy neutrino astronomy is similar to that for solar neutrinos and supernova neutrinos; namely, as a signal of what goes on deep inside a source region. High energy neutrinos are produced primarily from decay of charged pions, which in turn are produced when accelerated protons and nuclei interact with matter near their sources or in the interstellar medium. In fact the production spectrum of neutrinos from decay of charged pions is very nearly equal to the production spectrum of photons from π^0-decay. However, in a dense source region, the photons are easily absorbed. The ideal, therefore, would be to study both neutrinos and photons from the same source to map the distribution of matter relative to the cosmic accelerator and beam. In addition, the detection of neutrinos and photons from the same source would confirm that the photons are indeed produced by collisions of accelerated ions rather than by radiation from accelerated electrons.

This subject has a long history, but is still in its infancy. Markov and Zheleznykh (*48*) first developed the idea of using ν-induced upward muons to search for ~TeV neutrinos from extraterrestrial sources. In his 1960 review of neutrino physics (*49*), Reines distinguished between neutrinos produced by cosmic ray interactions in the atmosphere and truly "cosmic" neutrinos of extraterrestrial origin. He described a large water detector to study "contained" ν-interactions, and he calculated that a volume of about 5000 metric tons would be needed to obtain one interaction per day induced by neutrinos of atmospheric origin, which he called "cosmic ray" neutrinos. This concept was realized in this decade by the IMB and Kamiokande experiments. Greisen (*50*) also mentions the idea of neutrino astronomy as a "fanciful proposal" in his 1960 review of air shower physics.

Atmospheric neutrinos were first measured by seeing neutrino-induced muons emerging from the rock at angles so large that they could not be muons penetrating from the surface (*51*). The concept is illustrated in Fig. 7, which shows neutrinos interacting at an underground detector. Most interactions of muon-type neutrinos produce muons. Energetic muons have a long range, so the detector volume is effectively enhanced from $(\text{area})^{3/2}$ to (area) × (range). The fact that the muon range increases linearly with energy (up to ~1 TeV) is fortunate, because the flux of atmospheric muons with energies above several GeV is too low to give a significant number of events within the sensitive volume of present detectors. Large numbers of high energy atmospheric neutrino events have now been accumulated by five different underground detectors that measured upward or horizontal muons. The successful detection of atmospheric neutrinos in this way serves to calibrate it as a method for high energy neutrino astronomy.

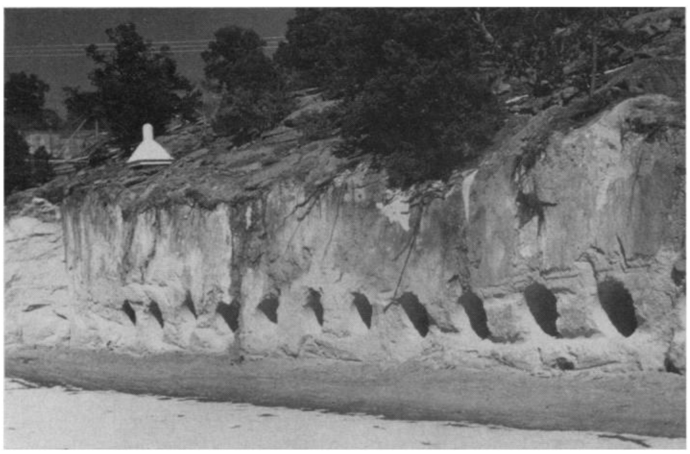

Fig. 6. Photograph of a portion of the "Cygnus" air shower array at Los Alamos showing drilling for underground muon detectors (courtesy of J. Goodman).

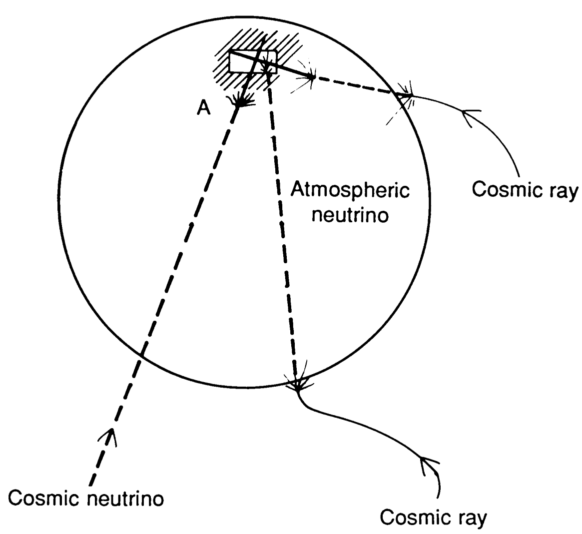

Fig. 7. Diagram that illustrates the idea of high energy neutrino astronomy by detection of upward or horizontal muons. Downward muons cannot be used for this purpose because the background of penetrating atmospheric muons is much too high, even at the deepest detectors.

So far, however, the only extraterrestrial neutrinos that have been detected are solar neutrinos (*52*) and neutrinos from the stellar collapse associated with Supernova 1987A (*53*). These neutrinos, with energies of ~10 MeV, have tiny cross sections but are sufficiently numerous to be (just barely!) detectable by their interactions inside the sensitive volume of the detectors.

The best upper limits on high energy neutrinos from point sources come from the two large water detectors (*54, 55*). The limits are generally stated in terms of neutrino luminosity at the source. They are approximately proportional to the square of the distance to the source (only approximately because some sources are in more favorable directions relative to the detector than others). For the present detectors, which have projected areas of a few hundred square meters, the limit for Cygnus X-3, for example, is several times 10^{40} erg s^{-1} in neutrinos alone. The total power in accelerated particles would have to be higher still and is far beyond what might be expected on the basis of the photon luminosity. One would therefore not expect to see a signal of high energy neutrinos with present detectors. Detectors with somewhat larger area are under construction at the Gran Sasso Laboratory in Italy. The detector MACRO, for example, will have about twice the area of IMB when seen from below, and it will have better angular resolution for upward muons.

The fundamental question for the future of high energy neutrino astronomy is, how much bigger do the detectors need to be to have a reasonable expectation of seeing a source? This is an old question, studied (*56*) in the context of the Deep Underwater Muon and Neutrino Detector (DUMAND) proposal. It is impossible to give a certain answer. The best one can do is to look to air shower measurements of point sources for guidance. The procedure is straightforward since the neutrino and photon production through pions are so closely related. Large uncertainties arise from uncertainty about the relation between accelerator, beam, and target in the sources—but this is one motivation for doing the measurements. Unfortunately, this is not the only source of uncertainty. The problematic nature of the air shower measurements themselves also limit the con dence one has in conjectures about the implied ux of neutrinos.

The DUMAND concept, which has evolved since its inception at the 1973 Denver Cosmic Ray Conference, has generated several related proposals and ideas. These include at least three proposals for detectors at the surface that could simultaneously measure downward air showers generated by photons and upward events generated by neutrinos (though not from the same source at the same time). There are two versions of the surface detector. One concept is the lake Gamma Ray And Neutrino Detector Experiment (GRANDE), which uses phototubes in water separated into several, optically isolated, horizontal layers. Upward muons would be distinguished by upward-going Cherenkov cones, whereas air showers would give a large electromagnetic signal in the top layer in coincidence with parallel downward Cherenkov cones generated by the penetrating muons. A similar proposal is under discussion in Italy. The other up/down concept is an electronic tracking detector (SINGAO) being tested in Italy to determine its feasibility for simultaneous gamma ray and neutrino astronomy.

As air shower detectors, both the GRANDE and SINGAO concepts differ from a conventional air shower array in that they see a large, continuous portion of the whole shower front rather than sampling it with widely spaced detectors. This allows a lower energy threshold and bigger dynamic range (for a given elevation), which in turn allows a measurement of an energy spectrum by a single experiment as well as a search for a threshold for possible anomalous behavior of photons.

A single DUMAND string has been tested and a nine-string array is planned. In addition, there is an experiment of the DUMAND type partially deployed in Lake Baikal. A novel DUMAND offspring is a concept (*57*) for an array of phototubes deep in Antarctic ice, which would use ice as the Cherenkov radiator rather than water. All these proposed detectors aim to have effective areas of at least 20,000 m^2, more than 40 times the existing detectors. With such a large area, the prospect for seeing a neutrino signal is good provided the original air shower and air Cherenkov signals from sources such as Vela X-1, Cygnus X-3, and Her X-1 can be taken at face value.

Conclusion

Gamma ray astronomy at ultra-high energies is presently in an uncertain state. Predictions for high energy neutrino astronomy also suffer because they are normalized to gamma ray signals. The potential implications of these subjects for the origin of high energy cosmic rays cannot be exploited until the persistent anomalies of the signals are understood.

The subject will receive clarification in the next few years from the experiments now under construction or expansion. Particularly important, in view of the sporadic nature of the signals from binary sources, will be simultaneous observation of the same outbursts seen with the same characteristics by two or more independent detectors. The "Cygnus" array at Los Alamos, the Chicago-Michigan-Utah experiment now under construction at Dugway, an array at Homestake, South Dakota, and the Whipple Observatory are close enough to each other for this purpose (*58*).

Another goal of fundamental importance is to lower the thresholds of the high energy experiments. Ultimately, one would like to have overlap between air Cherenkov experiments and satellite measurements on one hand and overlap between air Cherenkov and air shower experiments on the other. It is clearly desirable to map out the energy spectrum of a single source, such as the Crab Nebula and pulsar, from the GeV range to the highest possible energies. A second imaging telescope will be added at the Whipple Observatory (*59*). Together with the present 10-m reflector, it will form a Gamma Ray Astrophysics New Imaging Telescope (GRANITE) with a threshold of ~100 GeV. Proposed lake detectors have the potential to lower the threshold of air shower experiments. These initiatives, along with the several other new and ongoing experiments, have great promise for advancing the field.

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Ceramic Thin Films: Fabrication and Applications

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Ceramics are a distinct class of materials whose properties range from extreme hardness to unique electrical behavior. New methods of creating thin films of complex oxides and electronic ceramics allow the integration of these properties with semiconductor technology and raise the possibility of a new range of electronic devices.

POLYCRYSTALLINE CERAMICS HAVE BEEN WIDELY RECOGnized as important materials for both structural and electrical applications. Structural ceramics based on oxides, nitrides, and carbides are finding increasing use as mechanical components in engines and other machinery (*1*). Electrical ceramics range from passive oxides such as alumina (Al_2O_3) and silica (SiO_2) which are used as substrates and insulators in electronic circuits (*2*), to "active" oxygen-ion conducting zirconia (ZrO_2) which forms the basis for high-temperature oxygen sensors in automobile engines (*3*). More complex perovskite compounds such as barium titanate ($BaTiO_3$) and lead zirconate titanate are used in capacitors, electrically driven mechanical resonators, or electrically controlled optical switches (*4*). Such devices are widely employed as ultrasonic transducers and pressure sensors in medicine and engineering. The most recent development in electronic ceramics has been that of high critical temperature ceramic superconductors such as $YBa_2Cu_3O_{7-\delta}$ (*5*).

Ceramic coatings of alumina, silica, and titanium nitride prepared by the plasma spraying of powders onto a surface through a high-temperature gas plasma have long been recognized as an important method of resisting corrosion and minimizing wear (*6*). In recent years, other methods have been developed for the fabrication of thin films of more complex oxide ceramics. This article explores the major techniques used for this purpose and examines the opportunities that result for novel electronic devices and sensors.

The challenges encountered in fabricating thin ceramic films arise from the complexity of the materials in both composition and structure. For example, ferroelectric or piezoelectric properties arise in crystals when an internal electric polarization exists that can be modified by the application of mechanical or electrical stress (*7*). A mechanical stress then induces an electrical potential difference between electrodes or an electrical field causes a mechanical distortion of the crystal. The quartz phonograph pickup is the most commonly recognized application of this phenomenon. The effect arises in materials that have an asymmetric crystalline structure such that the center of electrical charge within the unit cell does not coincide with the center of mass. Examples of such materials are zinc oxide (ZnO), barium titanate, or lead zirconate titanate ($PbZrO_3$:$PbTiO_3$ often known as PZT). For the effects to be large the composition and the crystallographic structure of the crystal must be precisely defined. However, it is difficult to grow single crystals of these materials and they are often used as randomly oriented polycrystalline ceramics. In this case a net dipole orientation is induced by external "poling" with a high electrical field analogous to magnetizing a permanent magnet. Growth of a material as a thin film cannot only be used to fabricate complex ceramics on a scale compatible with semiconductor microcircuits, but can also provide a unique opportunity to create an internal crystallographic texture or epitaxial morphology (*8*). Figure 1 shows a film of zinc oxide that has been grown with the *c*-axis of the crystal structure tilted at a specific angle to a substrate (*9*). This allows specific combinations of longitudinal and shear acoustic waves to be generated for particular applications of an ultrasonic transducer (*10*).

A second form of crystalline complexity arises in the polycrystalline high critical temperature ceramic superconductors represented by $YBa_2Cu_3O_{7-\delta}$. The major factor that currently limits the use of these ceramic materials as practical superconductors is the current carrying capacity which is expressed as the critical current density J_c (amperes per square centimeter). This is primarily determined by the grain boundaries between the crystallites and secondarily by their alignment (*11*). The highest value of critical current in a ceramic superconductor has been reported in a thin film sample where the deposition process has been used to minimize grain boundaries and to produce a high degree of texture (*12*).

Integration of thin films of electronic ceramics with semiconductor technology has a number of interesting features. First, it broadens the range of sensing and signal processing elements available to the semiconductor designer, partly by enabling the amplifiers and conventional electronics required by the sensor to be

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