AN INTRODUCTION TO HIGH ENERGY ASTRONOMY

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ABSTRACT

Developments in the study of energetic charged and neutral cosmic rays are reviewed with an emphasis on recently published data. The interesting questions and ambiguities of the field are discussed at a level that should be comprehensible to the non-specialist.

INTRODUCTION

Any introduction to astroparticle physics must at least pay lip service to the variety of theoretically conjectured elementary particles and structures which might populate the cosmos. A sample of those entities which might provide observable consequences for experimental measurements is listed in Table I. To the best of my knowledge, there are no experimental confirmations for any of these objects. Clearly, nature has chosen to be rather parsimonious with the variety of her basic constituents.

TABLE I
Conjectured objects of astrophysical interest

antinuclei	mini black holes
axions	monopoles
cosmic string	newtorites
cosmions	photinos
4th generation fermions	strange matter
majorons	WIMPS

The remainder of this talk will concentrate on charged and neutral cosmic rays with an emphasis on energetic gamma-rays. The energy range will start at 10^{11} eV for which ground-based measurements are necessitated by the very small fluxes in our galactic neighborhood. Three years ago, Gabriel Chardin[1)] gave a pessimistic assessment of data from Cygnus X-3. This talk today is in the same spirit with the one exception that an astrophysical object, the Crab nebula, has now been unambiguously detected with ground-based instruments. The conference organizers requested both a pedagogical introduction to the field as well as a review of recent data. The emphasis here will be on the former, particularly since there have been relatively few significant results within the last year. I apologize for omitting discussion of data not yet published in referred journals but the field is already well polluted with many claims for marginal observations which have not been independently substantiated. For the interested reader, there are several recent review articles which cover the area of energetic γ-ray astronomy rather well. The status of VHE γ-ray astronomy was extensively discussed by Weekes[2)] in *Physics Reports* and a somewhat less comprehensive report on the UHE astronomy was written by Nagle, Gaisser and Protheroe[3)] for *Annual Reviews of Nuclear & Particle Science.* As an antidote for excessive optimism, the review of data from Cygnus X-3 by Bonnet-Bidaud and Chardin[4)] which appeared in *Physics Reports* is highly recommended.

CHARGED AND NEUTRAL COSMIC RAY DETECTION

Any understanding of ground-based cosmic ray observations must begin with the physics of detection. A highly energetic primary proton will make an initial collision with a nitrogen nucleus at an altitude of about 15 kilometers. The debris of this collision consists primarily of neutral and charged pions with successively smaller fractions of heavier particles such as kaons, protons, antiprotons, neutrons and so forth. The neutral pions decay immediately to γ-rays while the more energetic charged pions can undergo subsequent hadronic interactions to create additional π^{o}'s. For charged pions with energies less than about 12 GeV, the most likely fate is leptonic decay: $\pi^{+} \rightarrow \mu^{+}\nu_{\mu}$ or $\pi^{-} \rightarrow \mu^{-}\overline{\nu}_{\mu}$. A large fraction of the secondary muons will reach the earth's surface. The hadronic interaction probability for protons and air nuclei is characterized by an interaction length of 700 meters at sea level. A flight path through one atmosphere constitutes 11 interaction lengths.

For γ-rays, the interaction process is considerably simpler. A γ-ray passing near a nucleus of an air molecule will give birth to an electron and positron pair. Each of these charged particles will bremse energetic photons in subsequent collisions to spawn additional generations of $e^{+}e^{-}$ pairs. The probability for these processes is characterized by a radiation length of 300 meters at sea level. A flight path through one atmosphere constitutes 28 radiation lengths.

Since hadronic cascades continually feed energy into gammas via π^{o} decay, there is a great resemblance of hadronic showers to purely electromagnetic showers. One distinguishing feature is the presence of muons which are far less likely to be created by electromagnetic interactions. The small number of interaction lengths for hadrons transversing an atmosphere of air also leads to large fluctuations in the longitudinal and transverse distributions of secondary charged particles. Because the particle multiplication process is much simpler for electromagnetic showers, the longitudinal development for primary γ-rays can be estimated with reasonable accuracy by analytic methods.[5] The number of electrons and positrons versus atmospheric depth is shown in figure 1. The

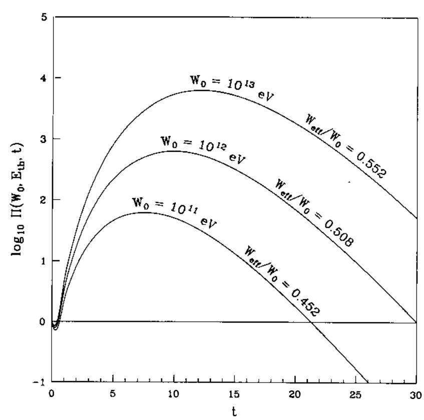

Figure 1. The longitudinal distribution of Čerenkov light emitting charged particle tracks for showers initiated by γ-rays of energy W_0. $\Pi(W_0, E_{th}, t)$ is the number of charged particles above the Čerenkov threshold at atmospheric depth, t.

qualitative behavior for hadronic showers is quite similar.

Two methods for detecting cosmic ray cascades are shown in figure 2. Air showers with primary energies in excess of 10^{14} eV propagate a sufficient number of electrons to the earth's surface to permit detection by modest arrays of scintillation or ionization detectors. The incident shower direction can be measured to a precision as high as 0.5° by sensing the relative time of arrival across the array. Even with a relatively small investment in equipment, showers can be recorded which impact anywhere within a radius of several hundred meters.

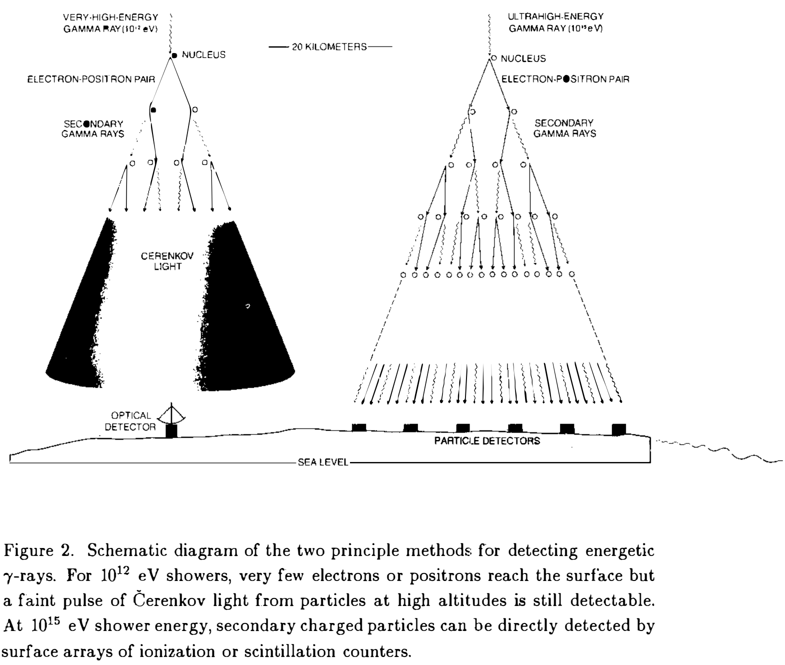

Figure 2. Schematic diagram of the two principle methods for detecting energetic γ-rays. For 10^{12} eV showers, very few electrons or positrons reach the surface but a faint pulse of Čerenkov light from particles at high altitudes is still detectable. At 10^{15} eV shower energy, secondary charged particles can be directly detected by surface arrays of ionization or scintillation counters.

Showers with lower energy can still be detected at the earth's surface by sensing the Čerenkov light radiated by the fraction of relativistic electrons and positrons that exceed the threshold energy. For electrons at sea level, this is 20 MeV. This technique is useful for cosmic ray primaries in the energy range, 10^{11} to 10^{13} eV. The Čerenkov signal is exceedingly faint so that detection is restricted to clear, moonless nights. The sensitive area is restricted to an impact radius of 100 meters beyond which the light flux becomes too faint to be detected against the night sky background. A variation of the Čerenkov technique permits the detection of ultra high energy showers by measuring the nitrogen fluorescence light from charged particle excitation. Because the photon emission is isotropic, showers can be sensed at much larger distances, up to several kilometers. This method is embodied in the Fly's Eye detector[6] in Utah where two large arrays of photomultipliers stare at the entire sky. Stereoscopic reconstruction of the light emission permits complete determination of the shower trajectory. The large integration area provides the sensitivity to detect cosmic rays out to 10^{20} eV, the highest ever recorded.

CHARGED COSMIC RAYS

The two outstanding questions of cosmic ray physics are the origin of the energy spectrum and the nature of the charged particle constituents. The energy spectrum[7] is shown in figure 3 for energies up to 10^{20} eV. The overall behavior can be approximated by a power law. By multiplying the differential flux by $E^{5/2}$, the vertical scale can be considerably compressed[8] as shown in figure 4. A clear break appears at about 10^{16} eV. The change of slope may be due to an evolution of the constituent primary particles from protons to heavier nuclei with leakage of lighter particles from the confines of the galactic magnetic field. The flux at the very highest energies[9,10] is shown in figure 5. No events have been found above 10^{20} eV, consistent with the Greisen prediction[11] of a cutoff induced by photonuclear interactions of protons with the cosmic 2.7° microwave background radiation. Understanding the origin of the most energetic cosmic rays has not been easy. Conventional shock wave acceleration mechanisms fail to generate particles above 10^{15} eV. Studies of ^{10}Be abundance in lower energy cosmic rays have provided an estimate of 10^7 years for the galactic magnetic containment time.[12] It is not understood how the upper end of the cosmic ray spectrum can be generated by shocks within such a short interval.

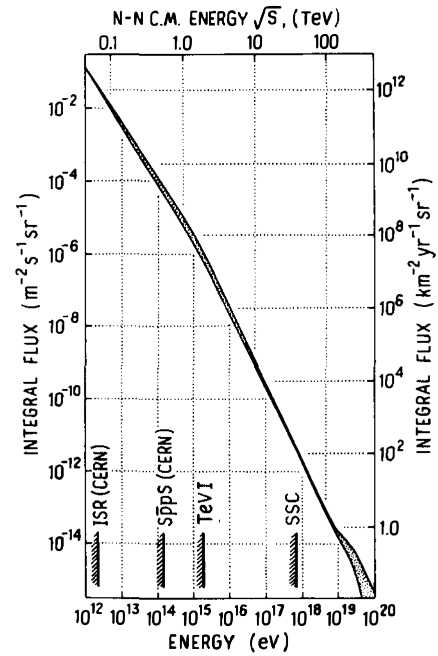

Figure 3. Cosmic ray integral energy spectrum above 1 TeV (from ref. 7).

Some of this mystery would be diminished if the highest energy cosmic rays turn out to be heavy nuclei. Experimental access to this question is provided by two different kinds of measurements. EAS experiments that distinguish muons and electrons on an event-by-event basis can estimate the atomic weight of the primary particle. As shown in figure 6, the

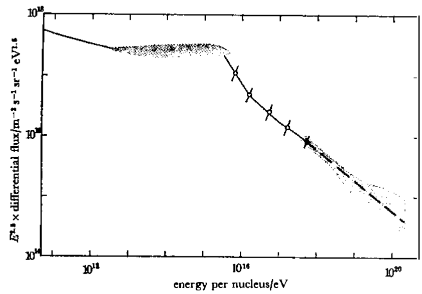

Figure 4. The cosmic ray differential energy spectrum. The flux has been multiplied by $E^{2.5}$ to compress the vertical scale (from ref. 8).

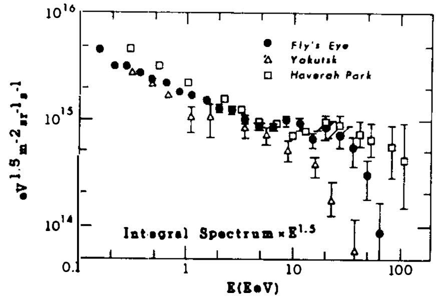

Figure 5. The cosmic ray integral energy spectrum near the endpoint of 10^{20} eV (from ref. 9).

heavier primaries produce, on average, a larger number of muons.[13] Since fluctuations from event to event are large, this method requires sizeable data samples. The results also must rely on the validity of the Monte Carlo simulation of shower generation and detector response. A more direct technique is to observe the average atmospheric depth of the shower maximum and infer the total interaction cross section. Data from the Fly's Eye[14] are shown in figure 7. The authors conclude that the data is inconsistent with one single constituent. In their view, the very highest energy cosmic rays are neither purely protons nor purely heavier nuclei.

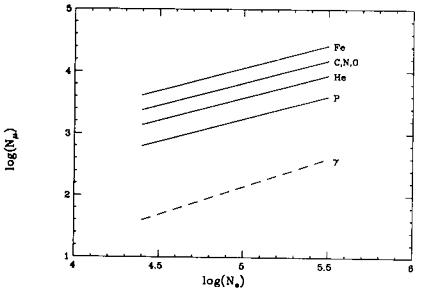

Figure 6. A Monte Carlo estimate of the number of muons generated by a UHE air shower as a function of the number of electron for various cosmic ray primaries (from ref. 13).

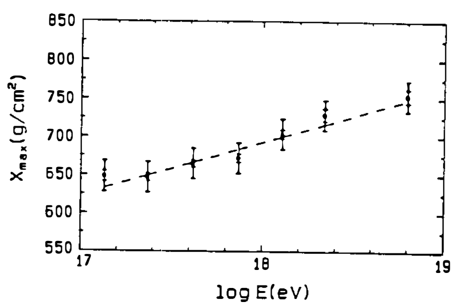

Figure 7. Depth of shower maximum as a function of energy (from ref. 10).

The ambient galactic magnetic field of approximately one microgauss randomizes the arrival direction of charged particles over distances given by:

$$d(kiloparsecs) \simeq \frac{E(eV)}{10^{18}Z} \tag{1}$$

It is not surprising that the cosmic ray flux is isotropic (although some asymmetry might have been expected at the highest energies). If cosmic rays are accelerated in a highly localized volume, that location is hidden from us by the labyrinthine trajectories of charged particles which reach the earth. This question could be resolved if the source of energetic cosmic rays also generates γ-rays whose flight path is undisturbed by intervening magnetic fields. The average intensity of such γ-rays cannot be large as shown by the following argument: Assume that high energy protons and γ-rays are created in equal numbers. Protons are contained within the galaxy for about 10^7 years while the γ-rays free-stream outwards with a typical residency time of 1000 years imposed by the galactic disk thickness. From this naive estimate we would expect a γ-ray to charged particle ratio of the order of 10^{-4}.

For almost all ground-based detectors the magnitude of reported γ-ray fluxes is characterized by:

$$I(>E) = \frac{4 \times 10^{-11}}{E(TeV)} \; \gamma/\mathrm{cm}^2 - \mathrm{sec} \tag{2}$$

Although this nominal flux principally reflects the sensitivity limits of current detectors, we will assume for the moment that this flux reasonably approximates the radiation from objects such as Cyg X-3. The total energy flux at earth's surface can be estimated by integrating over a broad energy band. The characteristic value is 10^{-5} ergs/m^2-sec. The luminosity of the parent object must be:

$$L \simeq 10^{37}\left(\frac{R}{10\ Kpc}\right)^2 \quad \mathrm{erg/sec} \tag{3}$$

where R is the distance to the source. The luminosity is bounded from above by the Eddington limit which is a statement that radiation pressure on infalling material cannot exceed the gravitational forces driving the accretion. This works out to be:

$$L_{edd} \simeq 1.4 \times 10^{38}\left(\frac{M}{M_\odot}\right) \quad \mathrm{ergs/sec.} \tag{4}$$

Galactic sources with the "standard" luminosity given by equation 2 will not violate the Eddington limit but significantly brighter objects will engender difficulties. Such problems may be dismissed if the particular source is preferentially "beaming" radiation only in our direction.

Two models provide possible explanations for generating energetic particles including γ-rays. For an isolated pulsar, the magnetic axis and the spin axis are not necessarily aligned (see figure 8). The acceleration process is similar to the classical mechanics problem in which a sliding bead is constrained by a rigid rod rotating about a skew axis. In this case, charged particles are constrained transversely by the pulsar magnetic field so the only possible motion is parallel to the flux lines. Energy is transferred to the particles as they are thrown outwards. This mechanism is responsible for injecting high energy electrons into the Crab nebula to produce the observed copious flux of X-rays and γ-rays.

A more complex scheme is required to explain the acceleration of particles in the vicinity of compact binary systems. Both Her X-1 and Cyg X-3 appear to be neutron stars co-orbiting with normal companions which furnish a continual outflow of gas. The geometry of such systems is shown in figure 9. The mass transfer to the denser member generates energy at the rate of about 140 MeV per nucleon, sufficient to fuel the observed X-ray luminosity. It is less clear if particle energies above 10^{15} eV can be achieved unless the predicted shock wave acceleration is very efficient.

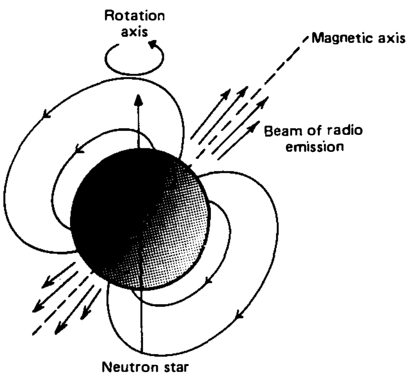

Figure 8. Schematic drawing of a neutron star whose magnetic axis is skew to the rotation axis (from ref. 12).

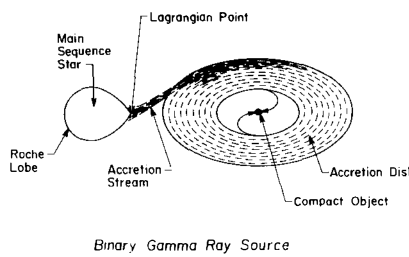

Figure 9. Schematic drawing of a binary stellar system containing a compact object such as a neutron star (from ref. 3).

CURRENT TOPICS IN RESEARCH

The current research goals of high energy γ-ray and ν astronomy are related to the two acceleration paradigms described above. The Crab pulsar is a good example of a young isolated neutron star. Measurements of its γ-ray flux above 10^{11} eV are consistent with inverse Compton scattering of energetic electrons on X-rays generated by synchrotron radiation in the surrounding nebula. This model should be more stringently tested. Now that the Crab has been reliably detected with ground-based instruments it has become an invaluable benchmark for testing improved equipment and analysis techniques.

Since binary systems with neutron stars such as Her X-1 and Cyg X-3 are suspected to be the origin of cosmic rays, considerable attention has been lavished on searching for their neutral radiations. When such observations become more reliable, the accretion disk acceleration model must be examined for consistency. The electromagnetic nature of the radiation must also be verified, particularly since it has been questioned by a number of experiments.

Geminga is an example of a curious star which radiates almost all of its energy in γ-rays. This object is relatively dim in X-rays and essentially invisible in the radio and visible wavelengths. Measurement at higher energies would add significantly to our understanding of the processes that drive its luminosity. Some have hoped that Geminga is but the first example of a new kind of exotic star.

The quasar, 3C273, is an extragalactic object observed with satellite instruments at energies up to 1 GeV. These measurements should be extended above 10^{11} eV to check if the flux behavior is consistent with a 10^6 solar mass black hole.

Various unusual compact binary systems have been studied at other wavelengths and invite subsequent investigation at γ-ray energies. As mentioned in the beginning, our theoretical colleagues have proposed a variety of interesting phenomena and some of these may also be amenable to detection by ground-based techniques.

As at longer wavelengths, the salient features of high energy neutral radiation are absolute flux, celestial position, time structure, and energy dependence. More accurate celestial coordinates are particularly important for identification of images obtained at longer wavelengths.

CRAB NEBULA AND PULSAR

The most solid evidence for γ-ray emission above 10^{11} eV comes from observations of the Crab nebula and pulsar by the Mt. Hopkins collaboration. Last year, they published results[15)] that demonstrated DC emission with a 9 σ statistical significance and subsequent data[16)] obtained with an improved Čerenkov imaging detector raised this to 15 σ. Our own group,[17)] working in New Mexico, has also seen a similar DC signal at the 6 σ level. These results have been achieved by using the larger transverse width of hadronic showers as a tag for rejection. The two groups have found no evidence for time structure on any scale. For example, Mt. Hopkins looked for month-to-month variations in the winters during the period, December 1986 through February 1988. The largest deviation was about 20%, consistent with the statistical accuracy of the measurement. A summary of the energy dependence of these results is plotted in figure 10. The high energy behavior is consistent with inverse Compton scattering of high energy electrons by X-rays. At energies up to 1 GeV, the Crab pulsar light curve has a distinct shape with two characteristic peaks. This is demonstrated by the COS-B γ-ray data[18] plotted in figure 11. No such modulation effects have been found either at Mt. Hopkins or by our own group. The upper limits for phased emission is about 4% of the DC flux at 200 GeV.

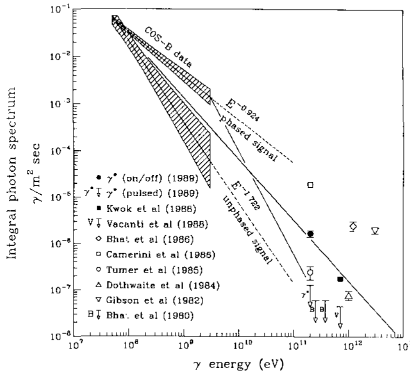

Figure 10. γ-ray flux from the Crab nebula and pulsar.

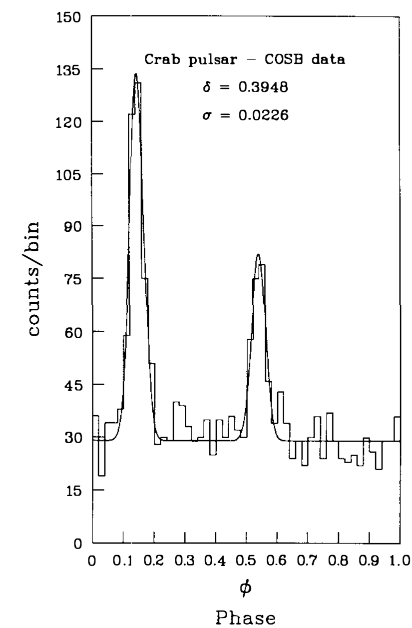

Figure 11. The Crab pulsar γ-ray light curve from the COS-B satellite data (from ref. 18).

If the DC flux is extrapolated to EAS thresholds, the flux would be around 10^{-15} γ/cm^2 – sec. This is an order of magnitude lower than current limits set by the UMC collaboration[19] in Utah, but such fluxes are within the capability of their array when completed by the end of 1990. Unfortunately if the inverse Compton model is correct, the energy spectrum will continue to steepen at higher energies and thus become completely undetectable at 10^{14} eV.

HERCULES X-1

One of the most well understood compact binary systems is Hercules X-1. Two people at this conference have made important contributions to our knowledge of Her X-1 and its companion, HZ Herculis. John and Neta Bahcall[20] were the first to identify HZ Herculis as the X-ray star companion by observing a optical brightening with the same 1.7 day periodicity as Her X-1. Paul Boynton and his group[21] have extensively analyzed the Her X-1 X-ray data to determine the physical conditions which modulate this system with periodicities of 1.24 seconds, 1.7 days and 35 days.

The most convincing evidence for high energy γ-ray radiation from Her X-1 was accumulated in May through June of 1986 by three independent experiments.[22–24] All three experiments observed short bursts of γ-rays with periodicities slightly shorter then the X-ray observations. The statistical significance is plotted in figure 12 over a narrow range of frequencies near the X-ray period. Although each experiment saw only one instance of strong periodic correlation and none of the observations were in time coincidence, the statistical probability appears remote for all three results to occur at the identical frequency by chance alone.

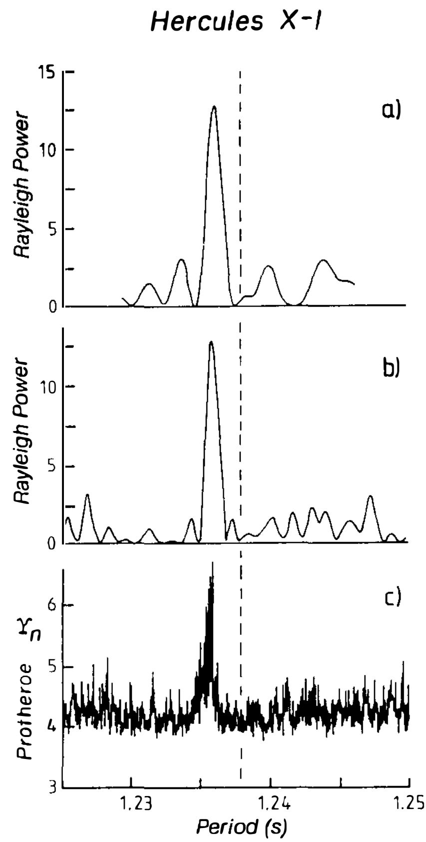

Figure 12. Three independent observations of γ-ray emission from Her X-1 at an anomalous frequency: a) Haleakala, 13 May 1986; b) Mt. Hopkins, 11 June 1986; c) Los Alamos, 23 July 1986 (from ref. 3). The dotted line marks the X-ray period.

The embarassing feature of these observations is that a more detailed examination of the data suggests that the signal is inconsistent with the expected behavior of γ-rays. At VHE energies, the transverse width of the Čerenkov images do not exhibit the narrowness expected for electromagnetic showers. For the EAS showers, the muon content appears to be at least as large as measured for hadronic events. Halzen[25] has attempted to explain these anomalies by suggesting that at very high energies the photon total cross grows substantially at energies greater than 1 TeV. More recent Monte Carlo calculations[26] show that this alone is insufficient to account for the observations. At accelerator energies the pair production cross-section is about a thousand-fold larger than the photonuclear cross section. Unless the photonuclear cross section grows large enough to compete, the first two or three generations of the shower cascade will almost always be electromagnetic. For the remainder of the cascade process, the secondary particle energies quickly drop into the energy range where the photonuclear cross-sections are well-known to be small. New physics is required if the propagation of these showers must be substantially altered from the normal electromagnetic cascade process.

Not much has been seen from Her X-1 since 1986. The Mt. Hopkins group[27] reported a signal phased exactly at the X-ray period in data taken 1986-1989 and our own group[28] found weak evidence for bursts at an anomalous frequency. This latter example is shown in figure 13. Neither of these results has compelling statistical significance. Observations will continue as sensitivity improvements of VHE and UHE detectors are realized.

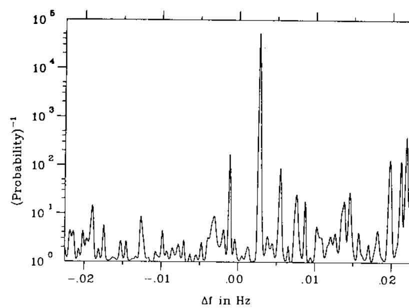

Figure 13. A possible observation of γ-ray emission from Her X-1 at an anomalous frequency. Data was obtained by the γ^* experiment in Albuquerque in 1988 and 1989.

CYGNUS X-3

The most anticlimactic source in the last few years is Cygnus X-3. After many fascinating scientific claims and much media attention, this source has had almost no new confirming evidence for the last four years. In desperation, one group[29] plotted the apparent flux as a function of calendar year and found an exponential decrease with a time constant of $1\frac{3}{4}$ years. It will require a major commitment on the part of our funding agencies to keep tracking an object with such a dim future!

For sometime the Durham group[30] has claimed to see a 12.59 ms modulation for VHE γ-rays with a 4×10^{-7} chance probability. Most of this evidence was accumulated in a total of one hour observing time in 1983. Mt. Hopkins[31] recently reported negative results with 35 hours of observing time. (In a recently published paper,[32] the Durham group has confirmed their original observations with new data taken in 1988 with an improved detector.) At EAS energies, the UMC collaboration[33,34] has looked unsuccessfully for muon poor showers from Cyg X-3. Their upper limits are plotted in figure 14. It was especially disappointing that no enhancement was found during the intense radio burst recorded in the summer of 1989. The Fly's Eye group[35] published evidence for neutral radiation from Cyg X-3 at energies above 5 x 10^{17} eV accumulated from 1981 through 1988. With similar sensitivity, Haverah Park[36] has seen no such effect during a similar period at a level at least $2\frac{1}{2}$ times lower.

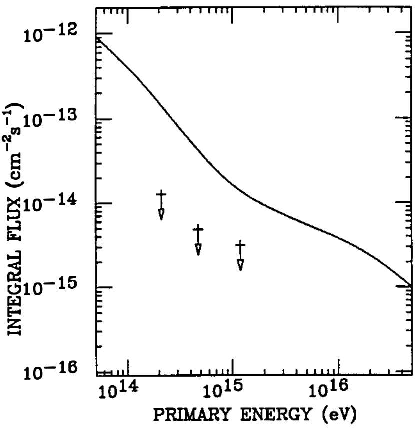

Figure 14. Upper limits on steady flux from Cyg X-3 obtained from muon-poor showers (from ref. 32).

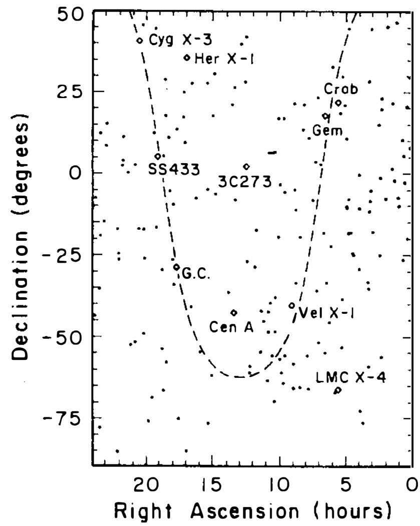

Figure 15. Arrival direction of upward-going muon events in the IMB detector (from ref. 36).

ν ASTRONOMY

Finally now, a word about neutrino astronomy. The IMB proton decay detector published results[37] a few years ago for upward-going muons from neutrino interactions. When mapped on celestial coordinates as shown in figure 15, no enhancement was found at any preferred location in the sky. The inferred upper limits corresponds to a ν/γ ratio of less than 1000 if the γ flux is assumed to be the canonical $\frac{4\times10^{-11}}{E}$ γ/cm^2-sec. How well will new proposed detectors perform under these circumstances? The IMB horizontal dimensions are 20 m x 20 m; the GRANDE proposal[38] envisages an area of 250 m x 250 m. Scaling sensitivity according to area, we see that GRANDE has a marginal chance for success if an object similar to Cyg X-3 can radiate a γ-ray flux with a magnitude near the canonical value given above.

CONCLUSIONS

As I stated at the beginning of this talk, my overall view of the present state of γ-ray and ν astronomy is somewhat pessimistic. The conclusions can be briefly summarized:

1. 10^{15} eV cosmic ray acceleration is not understood.

2. There exists at least one detectable VHE γ-ray source (Crab nebula).
3. No uniequivocal confirmation of radiation (VHE or UHE) has been found from X-ray binaries such as Her X-1 and Cyg X-3.
4. There is no compelling need for new or exotic particle physics.
5. The proper sensitivity scale for astrophysical ν experiments has yet to be determined.
6. By 1991, the sensitivity for γ-ray measurements will improve significantly with the completion of a variety of new detectors.

ACKNOWLEDGEMENTS

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