Very High Energy Gamma-Ray Binary Stars

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One of the major astronomical discoveries of the last two decades was the detection of luminous x-ray binary star systems in which gravitational energy from accretion is released by the emission of x-ray photons, which have energies in the range of 0.1 to 10 kiloelectron volts. Recent observations have shown that some of these binary sources also emit photons in the energy range of 10^{12} electron volts and above. Such sources contain a rotating neutron star that is accreting matter from a companion. Techniques to detect such radiation are ground-based, simple, and inexpensive. Four binary sources (Hercules X-1, 4U0115+63, Vela X-1, and Cygnus X-3) have been observed by at least two independent groups. Although the discovery of such very high energy "gamma-ray binaries" was not theoretically anticipated, models have now been proposed that attempt to explain the behavior of one or more of the sources. The implications of these observations is that a significant portion of the more energetic cosmic rays observed on Earth may arise from the action of similar sources within the galaxy during the past few million years.

AN EXCITING AND COMPLETELY UNEXPECTED PERSPECTIVE on the origin and distribution of cosmic-ray particles in the galaxy is coming from a series of ground-based observations that cover wavelengths in gamma-ray astronomy that are far beyond satellite capabilities. These extremely energetic gamma rays originate in the vicinity of neutron stars in binary systems. Although the processes by which they are produced are yet poorly understood, nevertheless they have the potential to give us direct and detailed information about the highest energy processes known in nature.

With the development of radio astronomy in the 1940s, astronomers began to explore parts of the electromagnetic spectrum other than the optical. The advent of space technology in the early 1960s led to the beginnings of x-ray astronomy; more recently satellite observations have begun the exploration of the ultraviolet and infrared bands, as well as the gamma-ray regime below a few gigaelectron volts (1 GeV = 10^9 eV). Since the early 1970s, a number of sources with photon energies from 1 TeV (1 TeV = 10^{12} eV) to 10 PeV (1 PeV = 10^{15} eV) have been detected with ground-based instrumentation. Each of these wavelength bands has made unique contributions to our understanding of the universe and its constituents. In this article we discuss the recent discovery of very high energy (VHE, 10^{11} to 10^{14} eV) and ultrahigh energy (UHE, 10^{14} eV and above) gamma rays from some neutron stars in x-ray binary star systems. More complete reviews can be found elsewhere (*1*).

At present there is no firm theoretical understanding of the mechanism or mechanisms by which the radiation is produced, although a number of models have been put forward. What is clear is that the progenitors of the gamma rays must be electrically charged particles with individual particle energies in excess of the energy of the photons observed. In most of the models the presence of a beam of ultrarelativistic protons or ions is postulated. In such models the gamma rays are produced through interactions of the beam with matter in the binary system, and portions of the beam that do not interact give rise to an enhanced population of energetic cosmic rays; a substantial fraction of the cosmic rays observed on Earth may be due to the combined effect of many such sources. The same objects might be also sources of other high-energy particles such as neutrinos.

Binary X-ray Pulsars

The term "binary x-ray pulsar" has now generally come to mean a pulsing neutron star that is accreting matter from a binary companion. (Strictly speaking, it can also apply to a binary system in which the compact object is a white dwarf, a collapsed star composed of electron-degenerate matter.) There are now more than 20 binary x-ray pulsars known (*2*), most of which are in our own galaxy. The x-ray pulse periods range from less than 0.1 second to about 1000 seconds. The Doppler shifting of the pulse frequency with time provides conclusive evidence for their binary nature. From the pulse frequency, the changes of that frequency with time, and the energy release, we conclude that the compact object involved is a neutron star.

The power developed by matter falling into a gravitational potential well of radius R is given by $GM\dot{M}/R$, where G is the gravitational constant, M is mass of the neutron star, and $\dot{M}$ is the mass accretion rate. For typical neutron star parameters the energy liberated (if the material falls all the way to the surface of the neutron star) is of the order of 10% of the rest mass energy of the infalling material; for sufficiently high mass accretion rates (10^{18} g sec^{-1}) the energy released surpasses the limit at which radiation pressure balances gravity (the Eddington limit).

The region around the neutron star (its magnetosphere) is complex and depends on the mass accretion rate, the magnetic field strength associated with it, its spin period, as well as the relative orientation between the spin and magnetic axes. A complete theoretical understanding of such systems even for isolated neutron stars (radio pulsars) has not yet been achieved. However, there is general agreement on the following picture: The infalling matter creates a hot disk of matter around the neutron star. If the magnetic field is sufficiently strong (10^{12} G at the poles of the neutron star), then the flow of material onto the neutron star is governed by the magnetic field pattern with the accreting material following field lines to

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either magnetic pole. X-rays modulated by the spin frequency of the neutron star are believed to arise from a beam pattern in which the magnetic axis is misaligned with the rotation axis. In this picture there is no prediction of very high energy gamma rays such as have now been observed nor is there any suggestion that x-ray binaries might also be a source of cosmic rays.

Techniques

At energies above about 100 GeV individual cosmic photons may be detected on the ground by virtue of the air showers that they create in the atmosphere. Figure 1 gives a schematic view of two air showers created by a VHE proton and by a UHE photon. From 100 GeV to roughly 10 TeV (the VHE region) the detection is generally by means of the Cherenkov light arising from the passage of the relativistic electrons and positrons through the atmosphere. The limiting Cherenkov angle for a charged particle traveling at the speed of light is 1.3 degrees at sea level and decreases as the square root of the atmospheric pressure (*3*). Because of this and because the direction of the shower particles tends to follow the direction of the initiating photon, the Cherenkov radiation is beamed in the direction of the incident photon over an area a few hundred meters in diameter on the ground. For a 1-TeV photon, the Cherenkov photon density within this pool of light is approximately 50 photons per square meter (*4*) with a time duration of less than 10 nsec. Typical Cherenkov receivers have mirror areas in the range of 5 to 100 m^2 and on clear dark nights can be used to detect the showers as electronic pulses by means of associated photomultipliers and high-speed electronics. The effective collection area of a Cherenkov receiver is $\sim 10^5$ m^2, the area of the pool of light.

A typical "bright" gamma-ray source of photons with energies in the TeV range can produce shower counting rates in excess of one per minute. In the absence of any other signature such as periodic emission, the presence of the source is indicated as an enhancement in the counting rate when the detector is aimed at the source compared to the counting rate when the detector is aimed off-source. The off-source background, due essentially to cosmic-ray air showers that are isotropic, may be as much as 100 times or more the signal rate. With these techniques such diverse sources as the Crab Nebula (a supernova remnant) (*5*) and Centaurus A (a bright radio galaxy) (*6*) have been reported.

At energies above 100 TeV (the UHE region), the detection of the photon showers is by means of the charged particle secondaries that survive to the ground. Arrays of 10 to 100 scintillators, each with dimensions of 1 m^2 and spaced at intervals of 10 to 50 m, have collection areas of 10^3 to 10^4 m^2 and can reconstruct the incident direction of the initiating photon to accuracies of 1 degree. Although the flux of photons decreases with increasing energy and the photon counting rate for UHE detectors is considerably below that of the VHE detectors, there is some compensation in that the higher energy detectors are not restricted to nighttime operation and they have a wide field of view. In the ideal case, a flux is detected first as a

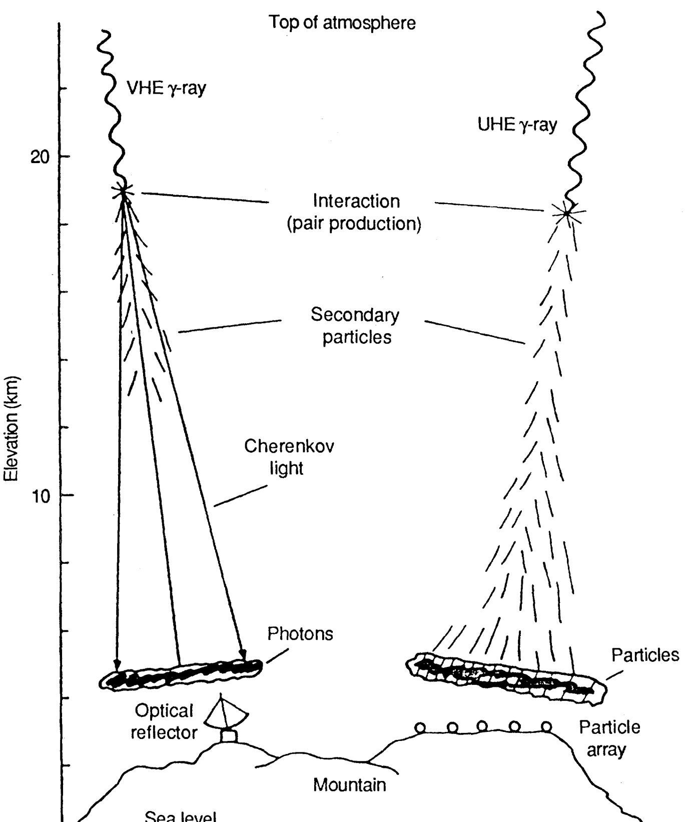


Fig. 1. Schematic view of two air showers created in the atmosphere. The VHE gamma ray is detected by the Cherenkov light emitted from the relativistic electrons and positrons of the shower. The higher energy UHE gamma ray creates numerous particle secondaries that penetrate to ground-based particle detector arrays.

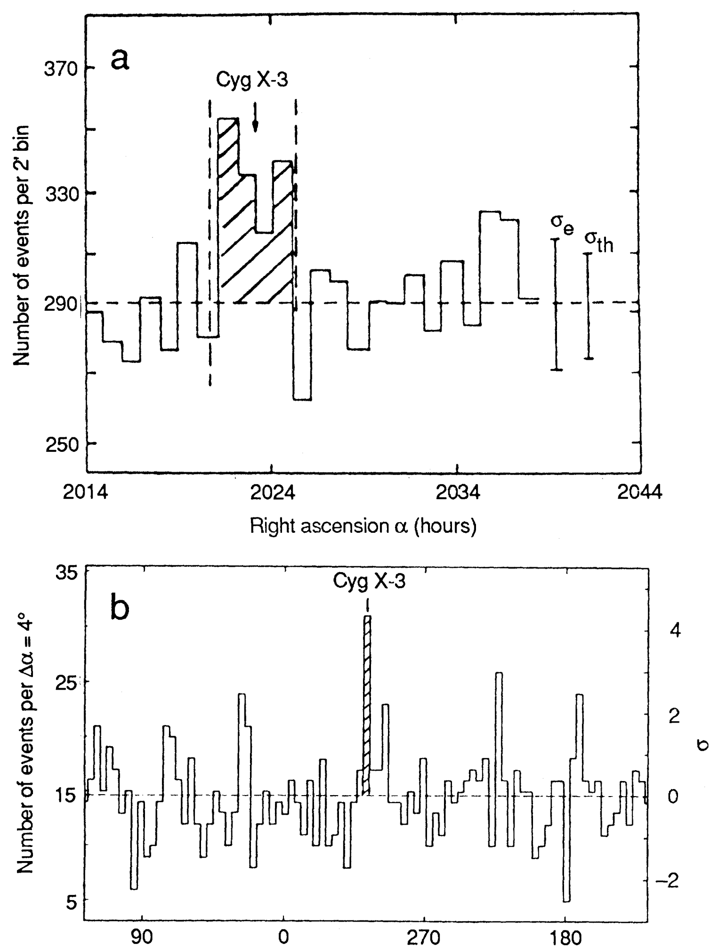
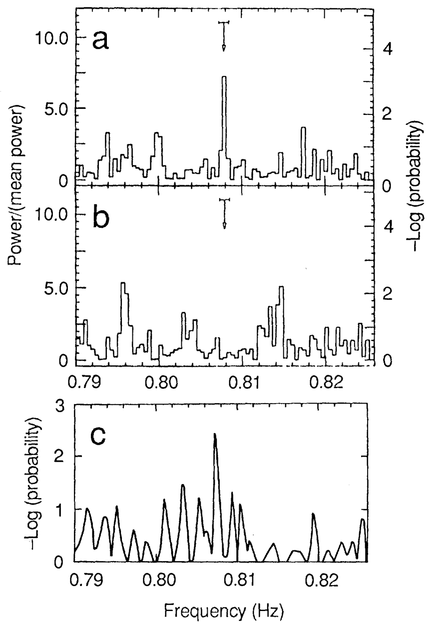


Fig. 2. First clear source detections at TeV and PeV energies. (**a**) Crimean Astrophysical Observatory observations in 1972 of Cygnus X-3 at energies of about 1 TeV (*7*). The standard error on the number of events in a bin has been derived in two ways: from counting statistics (σ_{th}) and from the experimentally observed fluctuations (σ_e). (**b**) University of Kiel observations of Cygnus X-3 from 1976–1980 at energies above 2 PeV (*8*).

Fig. 3. First simultaneous detection of TeV radiation by two independent groups. The source is Hercules X-1 with a known neutron star spin frequency of 0.808 Hz. The plots are segments of a Fourier analysis near the x-ray period. (**a**) and (**b**) refer to on-source and off-source Whipple Observatory data (*11*). An apparent signal at the x-ray period is observed, having a chance probability of about 10^{-3}. (**c**) Simultaneous observations by the University of Durham (*12*) at Dugway Proving Ground showing an apparent signal with the same frequency at a chance probability level of about 3×10^{-3}



net enhancement from the direction of the suspected source. This signal is then subjected to a periodicity analysis at the known rotation or orbital period of the neutron star. In some cases the net excess from the source direction is not statistically significant and the periodicity detection is the sole criterion for the detection claim.

Superficially the air showers that result from gamma-ray and cosmic-ray primaries are the same; however, in both the VHE and UHE ranges there are differences in the shower composition that are expected theoretically that can be exploited to increase the sensitivity of the gamma-ray telescopes to gamma-ray primaries. These differences arise because gamma ray–induced air showers are expected to have many fewer muons and to be significantly more confined laterally than comparable energy air showers from cosmic rays. In addition gamma-ray air showers reach their maximum development higher in the atmosphere.

The first clear source detections at TeV (*7*) and PeV (*8*) energies are shown in Fig. 2. The source, Cygnus X-3 in both cases, appears as a narrow angular enhancement above an otherwise smooth isotropic background from cosmic-ray air showers. In both of these cases the source detection was confirmed by the subsequent detection in the gamma-ray data of the characteristic 4.8-hour periodicity of the binary x-ray source.

Hercules X-1

The low-mass binary, Hercules X-1, is approximately 15,000 light years away in our own galaxy. It is multiperiodic, with a pulsar rotation period of 1.24 seconds, a binary orbital period of 1.7 days, and a 35-day modulation of unknown origin. In addition, the x-ray emission is observed to be nearly absent for long, irregularly spaced periods of time corresponding to what are known as "low states."

Of VHE and UHE sources that are firmly identified as binary x-ray pulsars, Hercules X-1 has been the most extensively observed. It was first detected as a VHE gamma-ray source in April 1983 by a group from the University of Durham, England, with an array of Cherenkov receivers located at the Dugway Proving Ground in Utah (*9*). A 3-minute counting rate excess was observed to be pulsed at the known spin period of the neutron star member of the system. In the spring of 1984, the Whipple Observatory Gamma Ray Collaboration began a program of monitoring Hercules X-1 at TeV energies. This collaboration consists of the Smithsonian Astrophysical Observatory, Iowa State University, University College, Dublin, and the University of Leeds; it uses the 10-m optical reflector (see cover) to detect air showers in the 0.1- to 10-TeV energy range (*10*). Eight episodes of emission were reported from 1984 to 1986 (*11*). These episodes were typically of duration 30 to 100 minutes, for a total of 7 hours out of the 140 hours of observation. One of the most remarkable of these detections (and one of the strongest) was after the neutron star had entered x-ray eclipse, clearly showing that the site of x-ray and the site of gamma-ray emission were not the same. Confirmation of one of the episodes of emission has been reported by the Durham group (*12*). The data from both groups for this simultaneous detection are shown in Fig. 3. The flux of photons with energies above 1 TeV during this episode was 3×10^{-10} cm^{-2} sec^{-1}.

Because of the low signal-to-background conditions that prevail at this time in VHE and UHE astronomy, a single detection of a possible source is generally not sufficient evidence that the source has emitted photons at very high energies. The detection of high-energy sources is further complicated by the fact that much of the emission appears to be variable in time with emission confined to a relatively small percentage of the orbital period. However, because there are 11 independent detections (two of which overlap and hence confirm each other), the case for the identification of Hercules X-1 as a very high energy gamma-ray star is strong.

A useful method to summarize the detections of Hercules X-1 at TeV energies and above is to locate them in time relative to the orbital period and the 35-day cycle. These times provide geometrical constraints on possible models (Fig. 4). This figure includes one episode of emission detected at energies in excess of 500 TeV in the Fly's Eye experiment operated by the University of Utah (*13*). During the 35-day cycle itself, there are two periods of time in which x-rays are observed and two periods in which they are not. These are referred to as "on" and "off" states, and are indicated on the figure. None of the 11 detections, with the exception of the eclipse episode at orbital phase 0.94, occurs during the 35-day off times. Three of the occurrences are near the beginning of the 35-day cycle and cluster near an orbital phase of 0.70. It is known from x-ray observations that the 35-day on cycle only begins at orbital phase 0.2 or 0.7 (*14*).

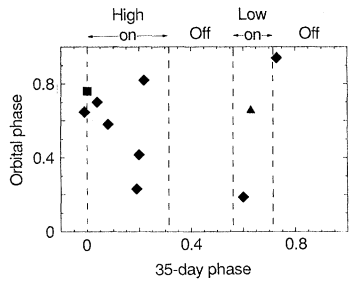
4U0115+63

The object designated 4U0115+63 (*15*) is a transient x-ray binary pulsar that has well-documented x-ray outbursts every 2 to 3 years. Its spin and orbital parameters are well known from x-ray observation during the outbursts; it is not a detectable x-ray source at other times. With its 24.3-day orbital period, the 4U0115+63 system (consisting of a 3.6-second spin-period neutron star and a >5 solar mass companion) is more than ten times larger than the Hercules X-1 system.

The University of Durham group first discovered TeV pulsed radiation from this source in September 1984 (*16*). The source was chosen for observation because it resembled Hercules X-1 in some ways. The periodogram obtained from nine nights of observations is shown in Fig. 5 with the periodicity range expected on the basis of x-ray observation indicated by arrows. The strong modulation in the periodogram at a period spacing of 0.15 msec is caused by the 24-hour observation cycle associated with the nightly observations beating with the 3.6-second period of the pulsar. This signal corresponds to a flux above 1 TeV of 7×10^{-11} photons per square centimeter per second.

Emission of TeV-energy photons from this source may have been

Fig. 4. Scatter plot of all observations of Hercules X-1, as a function of 35-day phase and 1.7-day orbital phase. The on and off states of the 35-day cycle are indicated. (■), University of Durham detection (*9*); (▲), Fly's Eye detection (*13*): and (◆), Whipple Observatory detections (*11*).



observed prior to 1982. In 1971–1972 the Crimean Astrophysical Observatory gamma-ray group (*17*) discovered a transient source in the constellation of Cassiopeia at energies exceeding 1 TeV. This source, labeled Cas Gamma-1, was detected twice in 2 years with emission lasting for about 30 days. There were no coincident x-ray observations. Because the position of this source lies close to 4U0115+63 and because of its transient nature, Cas Gamma-1 has been identified with 4U0115+63 (*18*). However, an alternative possible identification of Cas Gamma-1 with a recently discovered radio source, GT0116+622 (*19*), if correct, suggests that TeV astronomers have now encountered the problem of source confusion that other astronomers making limited angular resolution measurements face.

Vela X-1

Vela X-1, a Southern Hemisphere source, has a well-established orbital period of 8.96 days and spin period of 283 seconds. It is located at a distance of approximately 5000 light-years.

The University of Adelaide group (*20*) first detected Vela X-1 in the UHE band from observations taken during 1979–1981 by the Buckland Park air shower array in southern Australia. The emission was confined to a very narrow band of orbital phases (2% of the orbital period) centered at orbital phase 0.63. Because of the low counting rate (the observations correspond to total of 11 gamma rays) and the absence of good time recording, there could be no test of pulsation at the spin frequency. The emission corresponds to a flux above 3 PeV of 9×10^{-15} photons per square centimeter per second.

The University of Potchefstroom, South Africa, has recently reported evidence for VHE emission from Vela X-1 in which the 283-second spin modulation was observed (*21*). These observations indicated steady pulsed emission over the 2 months of observations as well as a remarkable outburst, lasting for just 90 seconds, in which the signal from the source direction was equal to the background rate. This outburst occurred just 4 hours after the x-ray source had entered eclipse by its companion star. As the authors point out: "This event is reminiscent of the TeV observations of Her[cules] X-1 just after the start of eclipse [*11*] and may be supportive of a recent model [*22*] postulating gamma-ray production by particle beams from the pulsar passing through the limb of the companion" (*21*, p. 569).

Cygnus X-3

At all wavelengths, Cygnus X-3 is an extraordinary object. Although it was one of the earliest x-ray sources discovered, it is still, after 20 years of research, one of the few strong x-ray sources about which there is major uncertainty. Conservative estimates of its distance place it on the edge of the galaxy at a distance of 30,000 light-years and give it an x-ray luminosity that makes it one of the strongest x-ray sources in the galaxy.

Cygnus X-3 was the first VHE and UHE sources to be discovered. It may be superficially similar to the other sources described above if it contains a rotating neutron star in a binary system. A spin period (12.6 msec) of the putative neutron star has been reported recently (*23*) from observations at TeV energies; this observation remains to be confirmed. If the observed value of the spin frequency is correct (it is a factor of 100 faster than that of Hercules X-1, the next most rapid binary pulsar observed at these energies), then the emission of VHE and UHE radiation from Cygnus X-3 may be due to a different process than that of the other binary pulsars. Cygnus X-3 differs in another respect, namely, the presence of radio emission at all times and the occurrence of giant radio flares during which its radio flux increases to 10^3 times its quiescent level (*24*). The characteristics of the radio outbursts suggest that they are associated with the emission of an expanding cloud of relativistic particles. Some correlation between the VHE gamma-ray emission and the large radio outbursts has been suggested (*7, 25*).

Cygnus X-3 has a well-established 4.8-hour periodicity (*26*), which is generally interpreted as the orbital period of a binary system. For each of the other sources we have discussed, Doppler shifting of the neutron star spin period identifies the orbital period of the system. For Cygnus X-3 we are lacking that conclusive evidence, so that the 4.8-hour period is open to other interpretations.

The distribution in phase of the extensive VHE and UHE observations of Cygnus X-3 is summarized in Fig. 6 (*27*). The observations have been plotted as a function of the 4.8-hour period for three different energy bands, 1 TeV, 10 TeV to 1 PeV, and greater than 1 PeV. At the lowest energies, the recent observations show emission at phases near 0.6, whereas, at the highest energies, the emission appears to be bimodal with emission dominantly near phase 0.2 but with some evidence for emission near 0.6 phase.

Representative flux values for Cygnus X-3 at TeV and PeV energies are as follows: Observations by the Crimean Astrophysical Observatory during 1972–1977 (*28*) correspond to a flux above 2 TeV of 1.4×10^{-11} photons per square centimeter per second. The University of Kiel discovery observation at PeV energies (*8*) indicates a flux above 2 PeV of 7.4×10^{-14} photons per square centimeter per second. However, Cygnus X-3 is a highly variable source at all observed wavelengths; unfortunately, the limited dynamic range of the VHE and UHE measurements precludes an accurate characterization of the variability for these energies. There is some evidence that the flux may be decreasing on a time scale of a few years.

In Table 1, we list the characteristics of each of the four sources

Table 1. Comparison of TeV binary sources.

Source	Time scale			Cyclotron line (keV)	Luminosity (erg sec^{-1})	
	Spin	Orbit	Precession		X-ray	VHE gamma rays
Hercules X-1	1.24 seconds	1.7 day	35 days	30 to 50	10^{35} to 10^{37}	10^{35} to 10^{37}
4U0115+63	3.61 seconds	24 days		11.5, 23	10^{33} to 10^{37}	10^{35} to 10^{36}
Vela X-1	283 seconds	8.974 days			10^{34} to 10^{37}	10^{34}
Cygnus X-3	12.59 msec?	4.8 hours	19.2 days?		10^{37} to 10^{38}	10^{35} to 10^{37}

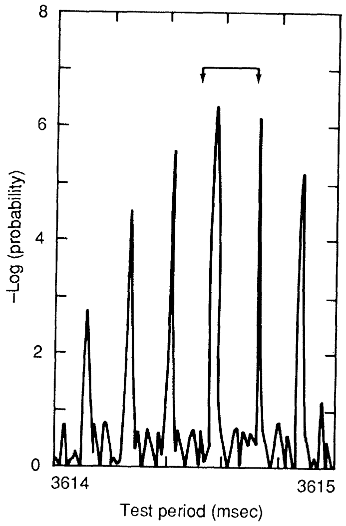


Fig. 5. Periodogram of the discovery observations by the University of Durham group of 4U0115+63 (*16*). The period expected on the basis of x-ray observations is indicated by the arrows. A strong signal having a chance probability of less than 10^{-6} is present. The modulation in the periodogram at a period spacing of 0.15 msec is caused by a 24-hour observation cycle that extended over the nine nights of observations.

accretion-disk electromotive force as the acceleration mechanism the strong magnetic fields of some of the sources may be a problem.

For most of the models the gamma rays that one observes on Earth are the result of beam-target interactions in which the target material is located somewhere in the binary system. Because of the extreme energies, the condition that the gamma rays strike the Earth requires nearly perfect alignment of the beam, target material, and the line of sight to Earth. The observation of emission from Cygnus X-3 at phases 0.6 and 0.25 (Fig. 6) therefore provides geometrical information about the relative orientation of the neutron star (the source of the beam) and the target. Various possibilities are discussed by Hillas (*29*). There is no reason to assume that a single location is to be expected in all cases. For example, the variation in orbital phases corresponding to emission noted for Hercules X-1 (Fig. 4) may arise from the interaction of the beam with targets at varying locations. With this interpretation, phase plots such as Figs. 4 and 6 may ultimately give geometrical details of binary systems that are unobtainable by other means.

that has been mentioned: the three well-established sources that are known to be x-ray binaries (Hercules X-1, 4U0115+63, and Vela X-1) and Cygnus X-3, which is well established as a VHE and UHE source, but whose binary nature is somewhat uncertain. One significant element common to the binary pulsars is the strong surface magnetic field of the neutron star. For the class of objects as a whole there must be a strong field (10^{12} G) in order to have funneling of material onto the magnetic poles and a consequent modulation of the x-rays, which is the result of a magnetic axis that is not aligned with the rotation axis. For both Hercules X-1 and 4U0115+63, there are measurements of the surface field inferred from the observation of spectral features in the range of 10 to 50 keV that are believed to correspond to radiation between quantized cyclotron levels. The field inferred for Hercules X-1 is approximately 5×10^{12} G (*2*) and for 4U0115+63 the field is 1.2×10^{12} G (*2*); these are the only x-ray binaries that have cyclotron lines that have been observed.

Models

The models that have been advanced to account for the VHE and UHE radiation have a number of distinctive elements, namely, the identity of the accelerated particle, the acceleration mechanism, and the nature of the radiation mechanism. At present there is no theoretical consensus regarding which model, if any, is correct. Table 2 summarizes many of the models that have been proposed. For a more extensive review the reader is referred to a report by Hillas (*29*). For the models that rely on the pulsar acceleration mechanism the relatively slow rotation rate of some of the sources is a problem. For those models that postulate either a shock wave or an

Cosmic-Ray Production

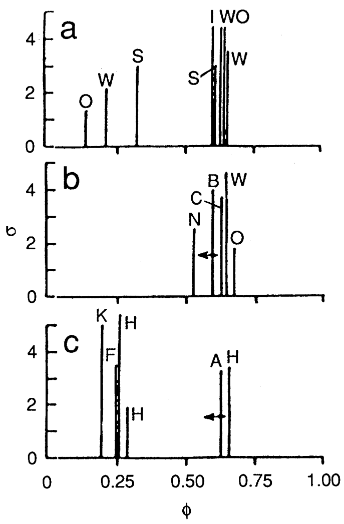
The most significant consequence of the detection of VHE gamma rays from these sources comes from a consideration of the total power that is implied to be going into VHE particles. This can be seen from a consideration of just the 1- to 10-PeV gamma-ray flux from Cygnus X-3. If isotropy is assumed, the gamma-ray luminosity is given by the equation $L = 4\pi d^2 eF$, where d is the distance to the source, e is a factor to account for absorption of the high-energy photons by the photons of the microwave background radiation (*30*), and F is the gamma-ray flux at Earth. For $d = 10$ kiloparsecs (kpc), $e = 3$ (*31*); and $F = 10^{-10}$ erg cm^{-2} sec^{-1}, then we find that $L = 4 \times 10^{36}$ erg sec^{-1}. This is close to the total x-ray luminosity (Table 1). If one takes into account that for only a small fraction of each orbital cycle are gamma rays seen (whereas for the entire cycle the cosmic-ray particles that produce the gamma rays are emitted) and that the efficiency for the conversion of cosmic-ray energy into gamma-ray energy is less than 10% (*32*), then the cosmic-ray luminosity $LCR = 4 \times 10^{38}$ erg sec^{-1}. Typically these high-energy particles would have energies some ten times greater, that is 10 to 100 PeV.

The power in cosmic rays in the galaxy in this band of energy can also be estimated. To maintain the observed flux in 10- to 100-PeV cosmic rays, $L_{CR} = D_{CR} V_G/t$ where D_{CR} is the observed cosmic-ray energy density ($\sim 4 \times 10^{-17}$ erg cm^{-3}), V_G is the confinement volume of the galaxy, and t is the confinement time. The latter two parameters are not known precisely at these high energies; however reasonable values are $V_G \approx 2 \times 10^{67}$ cm^3 and $t \approx 10^5$ years, which give $L_{CR} = 3 \times 10^{38}$ erg sec^{-1}. Thus only one source like Cygnus X-3 would be sufficient to maintain the observed cosmic-ray power at any given time.

Table 2. Models for TeV binary sources.

Beam	Acceleration mechanism	Radiation mechanism	Reference	Limitation
Electron	Pulsar	Bremsstrahlung	(*35*)	Rotation rate limits maximum energy to below what is observed for the slowest rotators.
Electron	Pulsar	Synchrotron radiation	(*36*)	
Proton/ion	Pulsar	π^0production	(*37*)	
Proton/ion	Shock wave	π^0production	(*38*)	Magnetic fields may be too strong
Proton/ion/neutron	Shock wave	π^0production	(*39*)	
Proton/ion	Accretion-disk emf	π^0production	(*40*)	

Fig. 6. Phase of maximum gamma-ray emission for Cygnus X-3 as summarized by Watson (*27*). The observations are plotted as lines as a function of the phase ϕ within the 4.8-hour period for three different energy bands: (**a**) TeV, (**b**) 10 TeV to 1 PeV, and (**c**) greater than 1 PeV with the height of an individual observation proportional to its significance (σ). The letters identify the observations as follows: W, Whipple Observatory; S, Stepanian; I, Riverside/Jet Propulsion Laboratory/Iowa State; N, Plateau Rosa; B, Khasmir; C, Baksan; O, Ooty; K, Kiel; F, Fly's Eye; A, Akeno; and H, Haverah Park.



The high-energy cosmic rays that are presently observed at Earth are probably unrelated to any of the above binary sources since the magnetic field of the galaxy prevents straight-line trajectories. For example, a 1-PeV proton has a Larmor radius in the microgauss magnetic field of the galaxy of the order of 1 light-year. Thus the propagation of such a cosmic ray through the galaxy is a diffusive process and therefore the time for it to traverse the galaxy may be much greater than the lifetime of any particular source. Cosmic-ray production in this picture is a dynamic process with many binary pulsars contributing for a comparatively brief epoch of their evolution.

Prospects

Taken at their face value these observations paint an interesting picture of a VHE gamma-ray sky that is highly variable and never dull. The objects that produce these high-energy quanta must be the most effective particle accelerators in the galaxy; their energy budgets suggest that they are far more efficient than our best man-made particle accelerators—and that they can reach energies a factor of a thousand greater than even the Superconducting Super Collider can achieve. There is much to be learned from the detailed study of such objects and it is not surprising that the number of ground-based gamma-ray observatories has quadrupled in the past 5 years.

However, we should remember that the discipline is still very young and many of the reported results are of small statistical significance. Verification of the most unusual effects are still necessary. A concern that one has for many of the observations is that the presence of pulsation has been utilized for the establishment of the existence of the source, rather than a confirmation of its identity. This arises when the excess counting rate from the source direction is not sufficient to independently establish the existence of the source.

A further concern arises as to the identity of the primary particle detected in these experiments. The relatively primitive telescopes used to detect gamma rays do not allow a unique distinction between photonic and hadronic primaries. Hence, although the telescopes are always designed to have the optimum sensitivity for gamma-ray detection, the identification of the detected signals with gamma-ray primaries is done by a process of elimination of all other possibilities. Those experiments that measure enough shower parameters to enable some crude selection of candidate gamma-ray showers (where the selection is made on the basis of predicted differences based on extensive Monte Carlo simulations of air shower development), do not show greater sensitivity than those that make no such selection. The conclusion then must be that the Monte Carlo simulations are incorrect or that some of the detections are in fact statistical fluctuations. A more radical explanation would be that the detected quanta are in fact not gamma rays but are some other form of neutral matter that only manifests itself at high energies. This is an exciting prospect for high-energy physicists but one that is highly speculative at this time. It is supported by the reported detection of Cygnus X-3 in underground experiments that were originally designed to measure proton decay (*33*). However, these results are still controversial and the detections have not been confirmed in other experiments with equal sensitivity (*34*). The simplest interpretation of the VHE and UHE observations is still that the primaries are gamma rays and that the selection techniques are poorly understood.

The construction of new and better gamma-ray telescopes is needed to provide improved sensitivity as well as overlapping observations. Some of these will be very large, the ANI project on Mount Aragats in Armenia, for example, and they will allow the unambiguous identification of the nature of the primary because of the many shower parameters measured. The launch of the Gamma Ray Observatory (GRO) by NASA in 1990 will be an added incentive to extend the sensitivity of ground-based detection techniques. Although the upper limit of EGRET (the Energetic Gamma Ray Experiment Telescope) on GRO will only be 30 GeV, it will be sufficiently close to the lower energy limit of the atmospheric Cherenkov technique (100 GeV) that complementary observations between satellite and ground-based telescopes will be of great value, particularly in increasing our understanding of the binary x-ray pulsars. These observations may determine whether these should more appropriately be called gamma-ray or even cosmic-ray binaries.

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Wind-Driven Ocean Currents and Ekman Transport

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Oceanographers have long sought to verify the theoretical Ekman transport relation, which predicts that a steady wind stress acting together with the Coriolis force will produce a transport of water to the right of the wind. In situ measurements of wind and ocean currents provide a detailed view of this phenomenon. By separating the wind-driven current from the measured total current and by averaging over a long record, it is found that the observed transport is consistent with theoretical Ekman transport to within about 10 percent. In this case the wind-driven transport is strongly surface trapped, with 95 percent occurring in the upper 25 meters as a result of fair summer weather.

THE STARTING POINT FOR MODERN THEORIES OF WIND-driven ocean circulation can be traced to Ekman's (*1*) theoretical study on the direct effect of wind stress on ocean currents. Ekman's theory was the first to acknowledge that vertical mixing in the upper ocean is caused by turbulence. He proposed that turbulent mixing could be modeled as a diffusion process, exactly analogous to molecular diffusion, but with an effective (kinematic) viscosity, A, many orders of magnitude larger than molecular viscosity. The value of A appropriate to the upper ocean was left to be determined from observations. By assuming that the momentum balance of a steady wind-driven current was between the turbulent stress caused by the wind and the Coriolis force caused by the earth's rotation, Ekman derived the archetypal solution for the vertical structure of a wind-driven current

$$[u, v] = \mathbf{V}_0 \exp(-z/D)\ [\cos(\pi/4 - z/D), \sin(\pi/4 - z/D)] \quad (1)$$

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where $[u, v]$ are, respectively, east and north current components; wind stress is assumed northward $[0, \tau]$; $\mathbf{V}_0 = \tau/\rho(Af)^{1/2}$ is the surface amplitude; $D = (2A/f)^{1/2}$ is the e-folding scale depth; z is depth taken positive downward; and ρ is the density of seawater that can be assumed constant. The Coriolis parameter f is equal to twice the vertical component of the earth's rotation vector, and in the Northern Hemisphere (assumed throughout), $f > 0$.

There are two noteworthy results from Eq. 1. The first is that the current profile from Ekman's theory has a spiral structure, called an Ekman spiral, in which current amplitude decays by one e-folding over a depth D as the current vector rotates to the right through 1 radian. Observations of ocean currents have often been fitted to this form in order to infer A, as Ekman suggested. Typical values are $D = 30$ m and $A = 500 \times 10^{-4}$ m^2 sec^{-1}. However, the range of inferred A covers more than an order of magnitude (*2, 3*) so that neither A nor D can be regarded as well known. The detailed specific structure of the spiral depends on A being constant in depth and time, which now seems unlikely to hold in the upper ocean (*2*). So-called turbulent Ekman theories have been developed to model the possible depth and time dependence of A (*4*). These theories yield somewhat different spiral structures, but there is no consensus on, for example, the sense of the depth dependence of A. The structure of the mean wind-driven current thus remains an open theoretical question.

A second and fundamental result from Eq. 1 is that the vertically integrated current, or volume transport per unit width, is given by the Ekman transport relation

$$\int_0^{z_r} [u, v]dz = [\tau/\rho f, 0] \quad (2)$$

where z_r is the depth below which the wind-driven current vanishes. If the Ekman spiral solution were applicable, then $z_r = 3D$ would be an excellent approximation. But just as D is not known beforehand with confidence, neither is z_r. However, the magnitude and direction of the transport follow directly from the presumed momentum balance between wind stress and the Coriolis force and are indepen-