EXTRASOLAR NEUTRINO ASTRONOMY

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SUMMARY

We may be on the threshold of the first detection of neutrinos beyond the solar system. Observations of >100 GeV γ-rays from x-ray binary systems strongly imply that these are natural accelerators of cosmic ray protons up to 10^5 TeV. Such protons can copiously produce neutrinos which propagate to earth where they may be detected in the next generation of underground and undersea experiments.

The best prospect for the first observation of extra-solar neutrinos is to search for point sources of ν_μ above 100 GeV. The detection principle is illustrated in Fig. 1: a neutrino from a cosmic source penetrates through the earth to the vicinity of an underground or underwater muon detector where it interacts with a nucleus in the surrounding material. At these energies muons can penetrate several kilometers of matter. Thus the effective detection volume is much greater than the actual physical volume of the instrument, with the earth or the sea around the experiment serving as the major part of the detector.

The muon direction can be measured to a precision of 1° or better and will deviate little from that of the initial neutrino at these energies. Thus the ability to locate a source is comparable to that of contemporary γ-ray astronomy. Measurement of muon energy to a precision of about 50% will be possible for detectors sufficiently large and well-instrumented to sample energy losses along the muon's path.

Neutrino telescopes are operationally different from conventional photon telescopes in at least one important respect: most of the sky can be continuously monitored by a single instrument. The telescope is not pointed at a particular part of the sky but looks in most directions most of the time. The instrument can be designed to continuously monitor the celestial sphere on time scales from microseconds to years. Random burst events which are missed because no particular photon telescope was looking that way at the time of the burst may be discovered, if visible in neutrinos. Sporadic and periodic sources can be studied without the great gaps in the record which plague most conventional observations.

In what follows the proposed mechanisms and possible sources of very high energy ν_μs are reviewed, with emphasis on the connection with very high energy and ultra-high energy γ-ray observations and cosmic ray acceleration models. It is shown that recent developments, both observational and theoretical, have increased the confidence that currently planned experiments with detection areas 10^3-10^4 m^2 will be able to detect neutrinos from x-ray binary sources, in our galaxy and possibly even in the neighboring Magellanic Clouds.

COSMIC SOURCES OF VERY HIGH ENERGY MUON NEUTRINOS

Extensive air showers with total particle energies as high as 10^{20} eV have been observed, implying that nuclei are being accelerated in the cosmos to energies far exceeding those for man-made accelerators on earth. The sites and acceleration mechanisms for cosmic rays have been a subject of intense study and debate since their discovery by Hess in 1912. A picture with at least two components of galactic cosmic rays is just now beginning to emerge[1]: at energies below 1 TeV protons and other nuclei are accelerated by the shock wave in a supernova explosion; above that energy nuclei, probably mostly protons, are accelerated in binary systems in which one of the bodies is a neutron star or other compact object. Recent observations of γ-rays above 100 TeV from a number of x-ray binaries have provided strong evidence for these as sources of the high energy component of galactic cosmic rays. As we will see, these binaries can be intense sources of muon neutrinos.

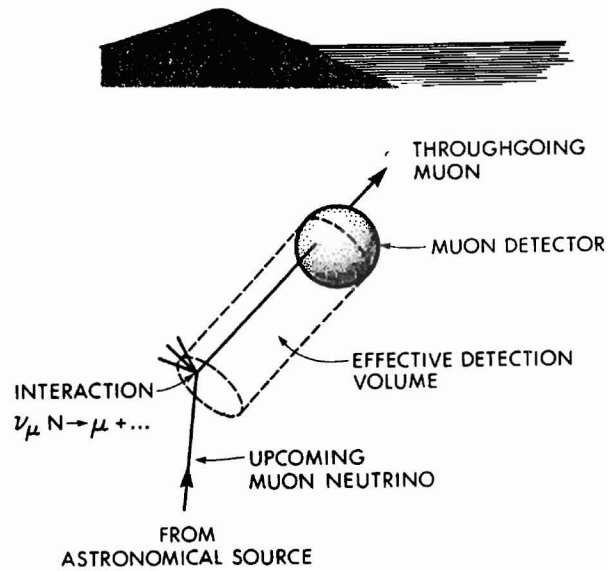

Fig. 1
The concept of a muon neutrino telescope: a very high energy muon neutrino from an astronomical source passes through the earth, interacting with a nucleus to produce a muon and any number of hadrons. The hadrons are quickly absorbed in the earth, but the muon can travel several kilometers before being stopped by ionization and radiative energy losses. Thus a large area muon detector, sufficiently deep in the ocean or earth to reduce the background from cosmic ray muons penetrating from the surface, can observe the muons from a volume much larger than would be practical to build, estimate their energies, and point them back to the source with an accuracy of 1° or better. The muon detector is shown ideally as a sphere and the angle between the muon and neutrino is greatly exaggerated for purposes of illustration.

The γ-ray connection

Charged particles in cosmic rays with energies below about 10^{18} eV are significantly deflected by the magnetic fields in the galaxy and so cannot be pointed back to their sources. This has been a primary factor in making the origins of cosmic rays so difficult to establish. In 1972 the Čerenkov light from air showers in the direction of the binary x-ray source Cygnus X-3 was found to pulse with the same 4.8 hour period observed in x-rays[2]. The directionality of the signal implied that the source particles are neutral, almost certainly γ-rays. The observation occurred just after a radio outburst from Cygnus X-3 and corresponded to an energy output of 3×10^{36} ergs/s above 1 TeV at the source, which is known to be at least 30,000 light-years away. This remarkable object, which can be seen in visible light by only the most sensitive optical

techniques, is perhaps our galaxy's most powerful emitter of energy from each of the two ends of the electromagnetic spectrum. Since then there have been a number of independent confirmations of Cygnus X-3, and several observations of other binary x-ray sources, using the atmospheric Čerenkov technique.

Other sources of 1 TeV γ-rays besides x-ray binaries have been confirmed, notably the Crab and Vela pulsars and the galaxy, Centaurus A.[3] The last is particularly remarkable, given its distance of 12 million light-years.

In 1983 extensive air showers pointing in the the direction of Cygnus X-3, recorded with particle detectors on the ground, were also reported to pulse with the same 4.8 hour period found at lower energies.[4] The energy of the particles producing these showers was at least 10^{16} eV. This has been viewed as direct evidence that at last a point source of cosmic rays had been found. Unlike the lower energy results, electron synchrotron energy losses in the magnetic fields known to be present make it likely that the mechanism for the production of these γ-rays is hadronic in origin, specifically neutral pion decay where the pions are produced in the interaction of protons and other nuclei with surrounding matter. This discovery was quickly confirmed[5] and other sources including Hercules X-1, Vela X-1 and LMC X-4 were soon announced.[6]

Underground muons from Cygnus X-3

Considerable attention has been focussed recently on the reported observations of underground muons in the general direction of Cygnus X-3, also exhibiting the characteristic 4.8 hour period, in two independent experiments.[7] Most surprisingly, the measured muon fluxes are comparable to the γ-ray flux above 1 TeV. Since γ-rays have a very low probability for producing muons, it is highly unlikely that the source particles are γ-rays. Neutrinos have also been ruled out as the progenitor of the muons by the fact that a signal is not seen below the horizon. If these observations are correct, then there is no conventional explanation;[8,9] suggested explanations have included photinos[10], gluinos[11] and quark-nuggets,[8] none of which is particularly compelling. Other underground experiments have so far failed to confirm the signals, although it is not clear whether these are inconsistent, given the variety of depths and different times of observation of what is known to be a very sporadic source. Whatever the ultimate disposition of this effect, it has stimulated a number of new independent theoretical studies of the compact binary system as an ultra-high energy particle accelerator and generator of photons, neutrinos and more exotic objects.

Proton acceleration in binary systems

Protons can be accelerated to extremely high energies in the vicinity of a compact object in several ways. A prototype neutron star with the parameters of the (non-binary) Crab pulsar has a magnetic field B ~ 10^{12} gauss at the surface and rotates with a period of 33 milliseconds (ms). The potential induced between the poles and equator by this rotating field can be ~10^{18} volts, sufficient to accelerate protons to the energies required. In general one would expect the ionized gas near the neutron star to short this potential, but empty regions, or "gaps" can exist in the magnetosphere in which a large potential difference can be maintained. It is generally assumed that the power source of Cygnus X-3 is a pulsar; however, until recently no evidence for a pulsar had been reported in any region of the spectrum. A 12.5 ms period in 1 TeV γ-rays from Cygnus X-3 was announced in 1985[12] and awaits independent confirmation.

Perhaps the x-ray binary system whose parameters are best known is Hercules X-1, whose compact component rotates with a comparatively slow 1.24 sec period. The kinetic energy contained in the rotation of this pulsar is not sufficient to maintain the observed luminosity for very long, so some other source of energy is required; most likely this is provided by gravity.

A way to harness gravity to generate the large electrical potential needed to accelerate particles to great energies was first suggested for the powerhouses in the nuclei of active galaxies.[13] In the case of a stellar-size system such as Cygnus X-3, protons can be accelerated up to 10^{19} eV by the electric field set up in the plane of the accretion disk, as the ionized matter pulled from the companion star spirals inward toward the neutron star.[14] Here the magnetic field B_s on the surface of the neutron star does not provide the acceleration; in fact, a low field is better since it allows the acceleration region to get closer to the surface. For $B_s \sim 5\times10^9$ gauss, protons can be accelerated to $\sim 6\times10^{18}$ eV with a maximum luminosity of 10^{41} ergs/s. However, in the case of Hercules X-1 where the neutron star field is 4×10^{12} gauss, this mechanism does not work.[15] Further, the model has problems in getting the accelerated protons out of the accretion disk across magnetic field lines.

In an alternate acceleration mechanism, protons and other nuclei are accelerated by diffusive shocks in the accretion flow.[16] In this scenario γ-rays (and neutrinos) are actually produced by neutrons, which are more readily able to escape the high magnetic fields in the acceleration region after being generated by nuclear collisions. These neutrons occur as the secondaries of interactions involving the original accelerated protons.

Obviously our knowledge of these truly super cosmic accelerators is still primitive, and it is possible that information from photons alone will not be sufficient to define the precise mechanism. The observation of muon neutrinos would produce unique information since, (a) they are produced by unambiguously hadronic processes and, (b) neutrino and photon production depend on different properties of the source.[17] Thus data from each will be highly complementary.

Mechanisms for γ-ray and neutrino production

Neutrinos and γ-rays will be produced when the protons accelerated in the vicinity of a compact object interact with matter either in the limb of the companion star,[18] or in material pulled from it by gravity.[14] This is illustrated in Fig. 2: protons interact producing pions, kaons and other hadrons which can initiate a cascade, dividing the energy among a larger number of particles. The neutral pions produced at any stage decay promptly into the observed γ-rays. If the density is not too high, the charged pions and kaons decay into muons and ν_μs before interacting, the muons then decaying into electrons, ν_es and ν_μs. Thus there is an intimate connection between the production of γ-rays and neutrinos. If the γ-rays being observed at the earth are produced by hadronic processes in the source, as is strongly implied by the observations, then ν_μs can be expected at comparable or even greater levels. Understanding the γ-rays gives us a handle, albeit an ambiguous one, on predicting the flux of neutrinos.

If the thickness of the matter along the line-of-sight to earth is an appreciable fraction of a radiation length (column density ~40 g/cm^2), γ-rays will be produced with an efficiency of about 10%.[17,19]

These γ-rays will initiate an electromagnetic shower which can regenerate photons at lower energies. In fact, the observed γ-ray power-law spectrum from Cygnus X-3 can be nicely explained by the electromagnetic cascade and synchrotron radiation which results when a monoenergetic beam of 10^{17} eV protons strikes matter a few radiation lengths thick.[20] A proton energy luminosity of $\sim 10^{39}$ ergs/s is required to give the observed flux, a million times the total energy luminosity of the sun at all wavelengths.

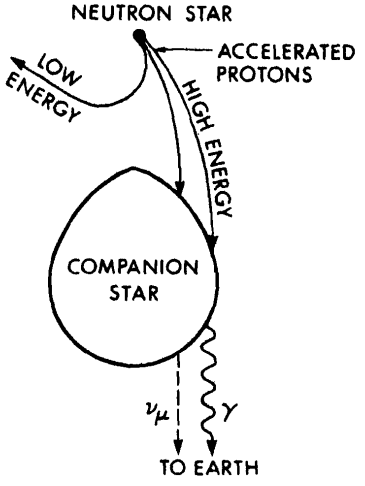

Fig. 2
An illustration of the production of γ-rays and neutrinos in a binary system. Protons accelerated by the neutron star strike matter pulled from the companion star or in its limb, producing pions and other mesons which decay giving γ-rays and neutrinos which then propagate to earth. The possibility that the proton beam is steered by the companion's magnetic field,[26] with the neutron star completely eclipsed and the lower energy protons failing to reach the star, is illustrated.

Because of absorption of γ-rays along the line-of-sight to earth it is possible that even this huge luminosity is an underestimate, with the result that a greater flux of neutrinos than γ-rays may exist. For systems such as Cygnus X-3 the proton luminosity can be as high as 10^{41} or 10^{42} ergs/s without being inconsistent with γ-ray observations or violating any known principles of astrophysics.

Promising Sources

Let us now look at several individual astronomical objects which are promising candidates for sources of measurable levels of very high energy ν_μs, based on the fact that γ-rays above 1 TeV already have been observed from these sources. Of course, Cygnus X-3 is the first to come to mind. If the ν_μ flux is comparable to that for γ-rays above 1 TeV, then a 10^5 m^2 detector such as proposed in the Deep Undersea Muon and Neutrino Detector project (DUMAND) would obtain a marginal 10-30 events per year.[17,19,20] However recent calculations tend to predict ν_μ fluxes 3-10 times higher.[22,23]

The γ-rays from Hercules X-1 are observed with about the same instantaneous flux as those from Cygnus X-3.[24] The search for signals from this source is aided by the better-known parameters, with x-ray periods of 1.24 seconds, 1.7 days and 35 days to be tested for neutrino periodicities. A remarkable new result shows the 1 TeV γ-rays from Hercules X-1 turning on during eclipse, that is, after the neutron star has passed behind its companion and the x-rays have shut off.[25] An explanation for this has been proposed in which the proton beam from the neutron star is steered around the edge of the companion by the latter's magnetic field,[26] as illustrated in Fig. 2. This will have important implications for the neutrino spectrum, cutting off the lower energies.

Recently a 1 TeV γ-ray signal from 4U0115+63, which is the x-ray binary closest to Hercules X-1 in luminosity, pulsar period, and pulsar spin-up rate, has been reported.[27]

Vela X-1 and LMC X-4 are two southern hemisphere 1000 TeV γ-ray sources which are particularly suitable for northern hemisphere neutrino searches, as the neutrinos pass through the earth to the detector. For sources in the Magellanic Clouds 150,000 light-years away, γ-rays at that energy will be attenuated by about a factor of 30 on their way to earth as they interact with the 2.7° photon background to produce electron pairs. This, together with the greater distance, implies that the proton luminosity of LMC X-4 is greater than estimated for Cygnus X-3, and that the neutrino flux will be at least 30 times greater than the measured γ-ray flux from LMC X-4. As we will see, this could make LMC X-4 detectable in the next generation of experiments. If Cygnus X-3 is a remarkable object, LMC X-4 may be even more so.

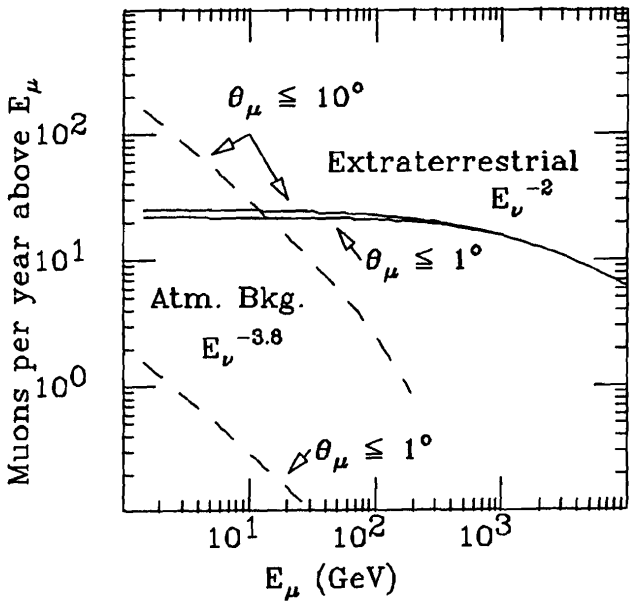

Fig. 3
The muon signal above an energy E_μ from an extraterrestrial source with an E_ν^{-2} spectrum normalized to give about 20 events per year (solid), compared with the background expected in a 1000 m^2 detector from atmospheric neutrinos (dashed). Two cuts on the muon angular separation from the source are shown.

THE DETECTION OF MUON FLUXES UNDERGROUND OR UNDERSEA

Any underground or undersea particle detector is a potential neutrino telescope, as illustrated in Fig. 1. A muon neutrino coming up through the earth is detected if it interacts with a nucleus in the earth, producing a muon which then passes through the detector. The detectability of a point source of muon neutrinos depends remarkably little on details of the specific instrument other than the effective detection area and muon angular resolution of the device.[28] The rather flat spectrum expected from extraterrestrial sources and the strong dependence of the effective volume of the detector on muon energy leads to events with muon energies mostly above 100 GeV, as seen in Fig. 3. On

the other hand, the background from atmospheric neutrinos has a much steeper spectrum and can be partially filtered out by setting a high muon energy threshold.

The dominance of high neutrino energies in the extraterrestrial signal has another important consequence which can be seen from Fig. 3: most muons in the signal are within 1° of the direction of their parent neutrinos. Thus good muon directional resolution in the instrument can increase the signal-to-noise as well as improve the location and identification of any discovered source. A 1000 m^2 detector with an angular resolution of 1° will have negligible atmospheric background - less than 1 event per year. A signal of perhaps five events in a 1° circle on the celestial sphere over the same time period would constitute the detection of an extraterrestrial source of neutrinos.

A very complete job of estimating the muon flux produced by neutrinos from Cygnus X-3 has been done by Gaisser and Stanev[23] using very detailed Monte Carlo simulations of the many processes involved both in the source where the neutrinos are produced and in the earth where the muons are generated; they estimate a muon flux of about one per year per 1000 m^2 of detector area. Thus it appears that a detector of 10,000 m^2 has a good possibility to see this source in neutrinos.

Existing and planned experiments

The large area (>100 m^2) underground and undersea muon detectors currently in use or under development are listed in Table I, along with the basic characteristics relevant to neutrino source detection. Also shown are the event rates which would be anticipated in each experiment for the maximum muon flux expected from Cygnus X-3 according to the estimate of Gaisser and Stanev. Most of these experiments were not designed primarily as neutrino telescopes.

The first five experiments listed have been in operation for some time and have reported only upper limits for extraterrestrial neutrino signals. Baksan,[29] located in the North Caucasus, is a large array of liquid scintillator detectors. IMB,[30] near Cleveland, and KAMIOKANDE[31] in Kamioka, Japan, are water Čerenkov proton decay experiments which also look at throughgoing muons. Frejus[32] is an array of flash tubes and Geiger planes which has been in operation since late 1984 in the Frejus tunnel between France and Italy. The solar neutrino experiment at the Homestake mine in South Dakota has been surrounded by liquid scintillation detectors arrayed on the surfaces of an 8x8x16 m^3 volume;[33] this has operated as an underground muon detector since 1985.

MACRO[34] is an approved multi-purpose array of liquid scintillators and other detectors, to be placed in the Gran Sasso tunnel in Italy, which will search for magnetic monopoles as well as muons and neutrinos. It is scheduled to begin full operation in 1988. The Lake Baikal Soviet DUMAND experiment[35] is an array of photomultiplier tubes which will be placed at the bottom of the giant Siberian lake. A single string of detectors is currently operating; ultimately a 400x200x300 m^3 array will be installed.

The Pacific Ocean DUMAND project is currently completing its first stage of development with the deployment of a single string of photomultiplier tubes suspended from a ship in deep waters near Hawaii. The TRIAD is an array of three similar strings of photomultipler tubes moored on the ocean bottom and attached to shore by an electro-optic cable which has been proposed as Stage II of this project.[36] If promptly approved, it could be operative by 1988. The full array would contain 756 photomultiplier tubes in an array 250x250x500 m^3 moored on the bottom with six electro-optic cables to shore.[21]

Of all these experiments, only the Lake Baikal and Pacific Ocean DUMAND full arrays would be capable of detecting neutrinos if they occur only at the same flux level as the observed 1 TeV γ-rays. If any of the smaller earlier experiments were to detect a signal, then the DUMAND experiments would be assured of a significant sample of data from which many important details about the source could be learned.

CONCLUSION

In conclusion, a new window on the universe is about to be opened with the advent of very high energy neutrino astronomy. Underground and undersea muon detectors should soon be capable of detecting muon neutrinos above 1 TeV from neutron star binary systems within our galaxy and the Magellanic Clouds. It is now clear that these very spectacular systems constitute natural particle accelerators which are far more powerful than any which can be imagined being built on earth. The information gained from the new science of neutrino astronomy will complement and extend our knowledge of the universe which up to now has been restricted to that gained from photons and the charged particles in primary cosmic rays. As with the opening of each previous window, we may look forward to exciting stories of new and unexpected phenomena being brought to us by neutrinos.

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Table I. The characteristics of existing and planned underground or undersea muon detectors with areas greater than 100 m^2. The first five are currently operating experiments. The remainder are in various stages of planning or preparation. The number of events per year expected from Cygnus X-3 using the estimates of Gaisser and Stanev[23] are indicated.

Detector	Depth (mwe)	Area (m^2)	Muon ang. res. (deg.)	Min. E_μ (GeV)	Events per year
Baksan[29]	850	256	2	1	0.33
IMB[30]	1570	390	7.4	2	0.50
KAMIOKANDE[31]	2400	130	2.7	2	0.17
Homestake[42]	4200	130	2.5	2	0.17
Frejus[32]	4500	115	0.5	0.3	0.15
MACRO[33]	4000	1400	0.2	3	1.8
TRIAD[36]	4500	3000	6	25	3.9
Lake Baikal[35]	1400	10^5	unk.	100	130
Pacific DUMAND Full Array[21]	4500	10^5	0.5	100	130