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ABSTRACT

There is now good evidence for astronomical sources of gamma rays above 300 GeV, detected by the atmospheric Cerenkov technique, and two apparent detections above 200 TeV with Extensive Air Shower arrays. New experiments now in operation or under construction should significantly improve the Cerenkov flux sensitivity. If very high energy cosmic rays are accelerated in compact regions, they can produce photons and neutrinos by hadronic interactions at levels which are detectable in current or proposed experiments. Observations of both gamma rays and neutrinos provide complementary information about the matter around the source and the proton source spectrum. The optimum conditions at the source for gamma ray and neutrino production by cosmic rays are determined and possible sources and source types are proposed. The status of the new funded DUMAND project, which hopes to detect very high energy astronomical neutrinos, is briefly reviewed.

INTRODUCTION

It is a fact that extremely high energy processes are taking place in the cosmos. Cosmic rays are observed to 10^{20} eV. But, except for the very highest energies where the fluxes are extremely low, the magnetic field of our galaxy effectively removes all directional information on the protons or other charged nuclei which constitute the bulk of cosmic rays.

It is possible that to fully understand the mechanism for cosmic ray acceleration we will need the information provided by neutral particles which can be pointed back to a source. In traditional astronomy photons are used exclusively; at sufficiently high energy, however, it becomes possible to seriously consider the use of neutrinos as a complementary window.

In this report observations of very high energy gamma rays will be reviewed. We will argue that very high energy neutrinos at comparable flux levels may exist, provided certain optimum conditions are present at the source. The results of calculations are presented which specify these conditions and indicate what fluxes may be expected from specific sources and source-types under these conditions. The Deep Undersea Muon And Neutrino Detector (DUMAND) project is capable of getting a signal if the fluxes exist at the levels calculated. The status of the project, now officially funded for its initial stage, is briefly reviewed.

VERY HIGH ENERGY GAMMA RAY ASTRONOMY

Observations To-Date

There are four sources for which statistically significant detections of photons above ~300 GeV have been reported from a number of experiments using the atmospheric Cerenkov technique.[1] The typical flux level is 0.1 km^{-2} s^{-1} above 1 TeV.

Table I. Statistically significant detections of very high energy gamma rays using the atmospheric Cerenkov technique.

Source	No. of Independent >3.5σ Detections	Highest Significance
Crab Pulsar	5	5.6σ
Vela Pulsar	2	4.2σ
Cyg X-3 Binary	3	5σ
Cen A Active Galaxy	1	4.6σ

While it is true that there are no very strong (10σ) effects, and the apparent variability of the sources together with the small duty factor of the observations makes confirmation difficult, there is little doubt that gamma rays of TeV energies are produced in some astronomical bodies. In particular, very convincing evidence is provided by the precise measurement of the period of Cyg X-3 which was later confirmed by x-ray data.[2]

Perhaps the most exciting observation, Cen A,[3] has not been independently confirmed; because of its presence in the southern sky, no one else has looked! The energy luminosity per decade observed around 1 TeV for Cen A is greater than any lower energy band from x-ray down to radio. In fact, Cen A sould be called a "gamma ray galaxy" rather than a "radio galaxy."

The following are the currently active experiments in very high energy gamma ray astronomy with the atmospheric Cerenkov technique:

1. Crimea, USSR
2. Tien Shan, USSR
3. Tata Institute at Ootacamund, India
4. Iowa St., JPL, Riverside at Edwards AFB, California
5. Durham at Dugway, Utah
6. Athens, Wisconsin, Purdue, Hawaii on Mt. Haleakala, Maui
7. Smithsonian, Dublin, Iowa St., Durham, Hawaii at Mt. Hopkins, Arizona

In addition, extensive air shower (EAS) arrays are turning their attention to gamma rays. In this case the threshold energy is of the order of 100 TeV, several orders of magnitude above Cerenkov telescopes, so the expected fluxes are much lower. Further, photons of such high energy will be strongly absorbed by pair production on the microwave background at extragalactic distances. Nevertheless sources within the galaxy may be detectable and recently a 4.4σ effect at a flux level of $(7.4\pm3.2)\times10^{-4}$ km^{-2} s^{-1} above 200 TeV from Cygnus X-3 has been reported[4] and independently confirmed.[5]

New Cerenkov Experiments

Improvements made to the 10m atmospheric Cerenkov system at the Fred Lawrence Whipple Observatory on Mt. Hopkins, Arizona should make a significant improvement, by about a factor of 10, in the gamma ray flux sensitivity.[6] A similar camera is now in operation in the Crimea experiment.[7]

Earlier observation with image intensifiers[8] have shown that the typical air shower Cerenkov image (photon or cosmic ray induced) is comet-shaped and a few degrees in size, in agreement with simulations. The Mt. Hopkins system uses an array of phototubes in the focal plane of the 10m reflector to reconstruct the image and determine its centroid and direction. Thus, the typical angular resolution of $\sim1^{\circ}$ is reduced to perhaps 0.2°. This, in turn, improves the minimum detectable flux by about a factor of five since the technique is mainly limited by the large background of cosmic ray-induced showers, about 1000x the rate of gamma ray showers. By repeatedly scanning over a suspected source, signals are detected above the fluctuations in the background. Imaging also makes possible a reduction in this background by utilizing some of the differences between gamma ray and proton showers.

The basic analysis procedure involves processing many thousands of shower images as the telescope either tracks the candidate source or drifts through it. No single event can be uniquely identified as a γ-ray or background cosmic ray proton. Rather a signal is detected by statistically comparing off- and on-source data.

Preliminary results indicate that imaging does indeed improve the flux sensitivity. A signal at the 3.17σ level has been seen from Cyg X-3 with imaging, compared to 0.73σ before the imaging algorithm is applied.[9]

The Mt. Haleakala experiment is still in the construction phase. It hopes to be able to reduce the energy threshold and reduce proton background substantially by the use of very fast circuitry. The light pulse from a gamma shower is much shorter than that for a proton shower, a few ns. Fast coincidence techniques can also make it possible to operate at a lower photoelectron level, and thus lower threshold energy.

PRODUCTION OF GAMMA RAYS AND NEUTRINOS BY COSMIC PROTON SOURCES

When high energy protons, or heavier nuclei, strike matter large numbers of mesons, mostly pions, are produced. The neutral pions will decay almost immediately into gamma rays. The charged pions will decay into muons and neutrinos; these muons, in turn, decay into electrons and neutrinos.

Gamma rays can also be produced by a number of electromagnetic processes which are not generally associated with cosmic ray protons and are not considered here.

If detectable fluxes of neutrinos are produced by these reactions, a new realm of astronomy would open up. In the last few years there has been a variety of suggestions of possible sources of neutrinos at both the galactic and extragalactic scale.[10] These possibilities divide into the usual classes: diffuse and point-like. Neutrinos produced by cosmic rays hitting the atmosphere generate a background which will determine the sensitivity of any neutrino telescope. Just as in other branches of astronomy, good angular resolution makes possible the detection of point sources at a much lower flux level than diffuse sources, and we will concentrate our attention on these.

Conditions for Maximum Photon and Neutrino Production

An attempt has been made to determine, with minimum model-dependence, the conditions for which very high energy gamma rays and neutrinos will be produced by hadronic processes (i.e., pion production and decay) in cosmic sources. Assuming a source of protons with a power law spectrum, the standard cosmic ray diffusion equations[11] are used to calculate the spectra and intensity of photons and neutrinos as these protons interact with the matter surrounding the source. The procedure is similar to that used by other authors[10-12]. The emphasis here is on extracting the general features, primarily concerning neutrino production.

The results can be illustrated in terms of an <u>efficiency</u> ε, defined as the ratio of the rate of production of photons or neutrinos in the energy band 1-2 TeV to the rate of incoming protons in the same energy band, after these protons have traversed a path length z gcm^{-2} of matter. In the calculation a power law proton spectrum of index α is assumed.

In Fig. 1 we show ε as a function of z for matter density $\rho < 10^{-8}$ gcm^{-3} and $\alpha = 2.3$. We see that the gamma ray production efficiency peaks at about 50 gcm^{-2}. As the path length of matter increases beyond the radiation length, $X_R = 60$ gcm^{-2}, photons are attenuated. By contrast, neutrino production builds up continuously as the protons pass through increasing amounts of matter, but an approximate plateau is reached above $z \approx 100$ gcm^{-2}. Significant neutrino production, at least 1%, of the proton flux, results for $z > 10$ gcm^{-2}.

The energy spectra of photons and neutrinos expected from a source is illustrated in Fig. 2. The gamma ray spectrum is found to have a spectral index equal to that of the incident proton, 2.3 in this case. To the extent that the assumptions made here apply, this implies that an observation of the gamma ray spectrum would directly give the shape of the source proton spectrum, information which is not readily available in the charged cosmic rays observed at earth.

We also note that the neutrinos decrease in intensity and their spectrum steepens as the density increases. Although not shown, at high densities the spectral index eventually becomes one unit greater than the proton source.

The analagous effect is observed for muons produced by cosmic ray protons hitting the earth's atmosphere. We can conclude that a measurement of the neutrino spectrum provides information about the matter density surrounding the source. Gamma ray and neutrino observations at very high energies are thus highly complementary, with measurements of their spectra and relative fluxes providing information on α, ρ and z.

The dependence of the neutrino production efficiency on α is shown in Fig. 3. We have assumed that the flattest source spectrum which can be expected has $\alpha = 2$. This would result, for example, from shock acceleration with neglible losses, and would lead to maximal neutrino production of 24%, under optimum conditions. On the other hand, the efficiency drops below 2%, for steep spectra. The gamma ray production efficiency is not as strongly dependent on spectral shape, as seen in Fig. 3.

The conclusion drawn from these results is that significant neutrino production at very high energies can occur when the source is a compact object surrounded by large amounts of matter, or intense magnetic fields which trap very high energy protons. Because of the large column densities of matter required, the best candidate sources are neutron stars or black holes on the stellar scale, and massive black holes at the centers of galaxies. In the case of neutron stars, or pulsars, sufficient matter is not likely to exist except in binary systems or during the early stages of a supernova.

Predicted Fluxes of Very High Energy Photons and Neutrinos

As mentioned, the typical flux sensitivity for the detection of gamma rays using the atmospheric Cerenkov technique is 0.1 $km^{-2}s^{-1}$ above 1 TeV.[1] For neutrinos above 1 TeV, the Deep Undersea Muon And Neutrino Detector (DUMAND) has an estimated minimum dectectable flux, for $\alpha = 2$, of 1 km^{-2} s^{-1}.[13] Let us define fluxes at these levels to be detectable.

In Fig. 4 we plot the proton luminosity $L_p(1)$ which is required to produce a detectable flux of gamma rays or neutrinos above 1 TeV from a source at a distance R, under the optimum conditions discussed in the previous section. Since the neutrino production efficiency is about 10x that for gamma rays, while the detectectable flux levels are in approximately the inverse ratio, each is coincidentally represented by the same line. From Fig. 4 it would appear that a stellar-size object within ≈ 50 kpc radiating ~10^{38} erg s^{-1} at TeV energies would be sufficiently energetic to produce detectable gamma rays or neutrinos, when the other conditions discussed above are met. Super-massive objects such as the black holes which may exist at the centers of active galaxies could have sufficient energy to be detectable at QSO distances.

Let us ask whether there is any evidence for proton luminosities at very high energies adequate to produce detectable photons and neutrinos. If the source of particle acceleration is highly efficient, such as in the case of strong shocks,[14] it will produce equal luminosites in all energy bands. Remarkably, this effect seems to be approximately consistent with observations in the electromagnetic spectrum, from the optical to gamma rays, for two main classes of compact objects we consider to be potential sources: pulsars and active galaxies. For example, the Crab has an electromagnetic luminosity of ≈ 10^{37} erg s^{-1} over the nine orders of magnitude in energy from 1 to 10^9 eV. On a waster scale, QSO 3C273 emits ≈ 10^{46} ergs s^{-1} over the same range in photon energy. Assuming that the electromagnetic spectrum results ultimately from the acceleration of protons and electrons in the source, we might expect L_p to be of the order of the measured L_{em}.

In our galaxy, the Crab and Vela pulsars have been observed in both the low [15,16] and very high[1] energy gamma ray bands. The electromagnetic luminosities implied by x-ray and gamma ray observations of these sources are plotted in Fig. 4. These fall approximately on the lines for detectable TeV gamma rays or neutrinos. We must hasten to add, however, that this does not constitute a prediction of measurable neutrino fluxes for these particular sources, but rather simply that we have at least two examples of pulsars with adequate energy production. We can take these as prototype neutron stars and imagine situations where there may be large amounts of matter in the vicinity of similar objects.[17,18].

QSO 3C273 has also been observed to emit low energy gamma rays[19], but only an upper limit flux has been set at 1 TeV.[20] As seen in Fig. 4, if the 1 TeV photon luminosity is the same as observed at lower energies, then TeV gamma rays are marginally detectable and neutrinos may be as well. This important result is in basic agreement with independent calculations.[21] To the extent that nearer objects such as Seyferts and radio galaxies are similar in nature, they may be observable. Since the power sources for QSOs and active galaxies are possibly supermassive compact objects in their nuclei, these represent perhaps the most interesting candidates for neutrino sources.[22,23]

Let us look at the two x-ray sources which have been fairly convincingly observed in the very high energy gamma ray region, but not yet at lower gamma ray energies: Cygnus X-3 in our own galaxy[24] and the radio galaxy Centaurus A.[3] The x-ray luminosities for these objects, which are consistent with the less reliable gamma ray measurements, are also shown in Fig. 4, indicating that these sources may have adequate power to produce photons and neutrinos by the mechanisms discussed.

The bands in Fig. 4 indicated the expected range of proton luminosities for the three generic source types considered: binary pulsars, early stages of supernovae, and active galactic nuclei. Any of the first type would be detectable in the galaxy and the second within the local cluster. The closer active galaxies may be detectable.

STATUS OF DUMAND

The Deep Undersea Muon And Neutrino project to build a giant neutrino detector in 4.5 km of water off the coast of the island of Hawaii has been under discussion for some time. After a three year feasibility study which demonstrated that such a detector could be built at a reasonable cost and that it would be a unique instrument for very high energy neutrino physics, astrophysics and cosmic ray physics, it is ready to move on to the first construction phase.

A collaboration composed of the Universities of Hawaii, California at Irvine, Purdue, Wisconsin, Kiel and Bern, the Institute for Cosmic Ray Research Tokyo, Cal Tech, and Scripps Institution for Oceanography has been formed to carry out the effort. The DUMAND proposal[13] has now obtained scientific peer approval from a committee formed by the U.S. Department of Energy, and initial D.O.E. funding for the first phase of construction. The estimated cost of the program is $12 million over five years, with non-U.S. contributions totalling approximately $2.5 million.

The concept of DUMAND can be summarized as follows: neutrinos produced either by cosmic rays hitting the atmosphere or from extraterrestrial sources interact in the ocean water or earth in the vicinity of the detector, producing muons. As a muon moves at a speed greater than the speed of light in water it generates Cerenkov light which is sensed by photomultiplier tubes. There are 756 of these PMTs arranged 50 m apart horizontally and 25 m apart vertically in an array occupying over 3×10^7 m^3. As great as this is, the effective volume for neutrino interactions is even greater since they can occur outside the array proper. It is also energy dependent; for 2 TeV muons the detector has an effective volume of almost 0.5 km^3.

The amplitude, width, and time of occurrence of the signal from each PMT is transmitted to shore over fiber optic cables at a rate of about 10^5 Hz per sensor. These data, plus the positions of the PMTs which are constantly monitored acoustically, are used to reconstruct the muon's direction with a precision greater than 1°, and its energy to 50-100%. Since the muon's energy is so great, its direction will not differ substantially from that of the incoming neutrino, and can thus be used to locate a source with accuracy comparable to gamma ray astronomy.

Despite the great size of the detector, the largest ever built for any purpose, the atmospheric background in the resolvable solid angle ($\sim 10^{-3}$ sr) is less than one event per year above 1 TeV. Thus a source which produces 10 events per year is detectable. The flux level required to do this is 1-2 km^{-2} s^{-1} above 1 TeV. As seen in the previous section, such fluxes are possible, if not likely, from compact objects surrounded by large amounts of matter.

DUMAND is, of course, not the first neutrino telescope. MeV neutrinos have been detected from the sun. DUMAND will not be sensitive to these. Further, the large underground detectors which have been built to search for nucleon decay will also look for extrasolar neutrinos. Indeed these experiments are ultimately limited by neutrino background. However, underground detectors are necessarily much smaller than DUMAND and are generally designed to operate at GeV energies where the angular resolution is poor and the atmospheric background is large. As a result, their sensitivities to extraterrestrial neutrinos with the power law spectra considered above is orders of magnitude worse than DUMAND, making the underground detection of the types of sources we have considered here unlikely. Of course we may all be happily surprised by the discovery of an unexpectedly high level of neutrinos since current limits on point sources are essentially non-existent.

CONCLUSIONS

The emission of gamma rays with energies in the teravolt region and higher is now confirmed observationally for a small number of sources. New experiments underway, in particular an imaging Cerenkov telescope on Mt. Hopkins, should soon tell us whether or not this is a common phenomenon. From general and (fairly) model-independent considerations it has been shown that the production of measurable fluxes of very high energy photons and neutrinos by cosmic ray protons near compact objects is a viable possibility. The most efficient production occurs when the spectrum is flat, as is expected from general considerations in several proposed cosmic ray acceleration mechanisms such as strong shocks. The predicted spectrum, E^{-2}, is in fact suggested by observations over the entire electromagnetic spectrum for a wide class of objects from pulsars to QSOs.

The fluxes of neutrinos we can expect from the sources considered would be at about the level of detectability of DUMAND. This project now has been approved for first stage funding. The large underground detectors built to explore nucleon decay are probably still too small and too poor in angular resolution to detect sources at the levels calulated here. Nonetheless data from these experiments are beginning to flow and will be analyzed for evidence of extraterrestrial neutrinos in the coming months.

If the predicted levels of neutrinos above 1 TeV are confirmed by future observations, then we would have strong and direct evidence that a major component of cosmic ray proton acceleration occurs in very localized regions of space buried deep in matter. Thus very high energy gamma ray and neutrino astronomy are highly complementary; electromagnetic observations by themselves can lead to ambiguous interpretations of the mechanisms involved. By a combination of observations on the fluxes and spectra of gamma rays and neutrinos from a particular source we can obtain the spectrum of the primary protons at the site of acceleration and the nature of the matter around the object. In doing so we will peer far deeper into the object than is possible by any other known means.

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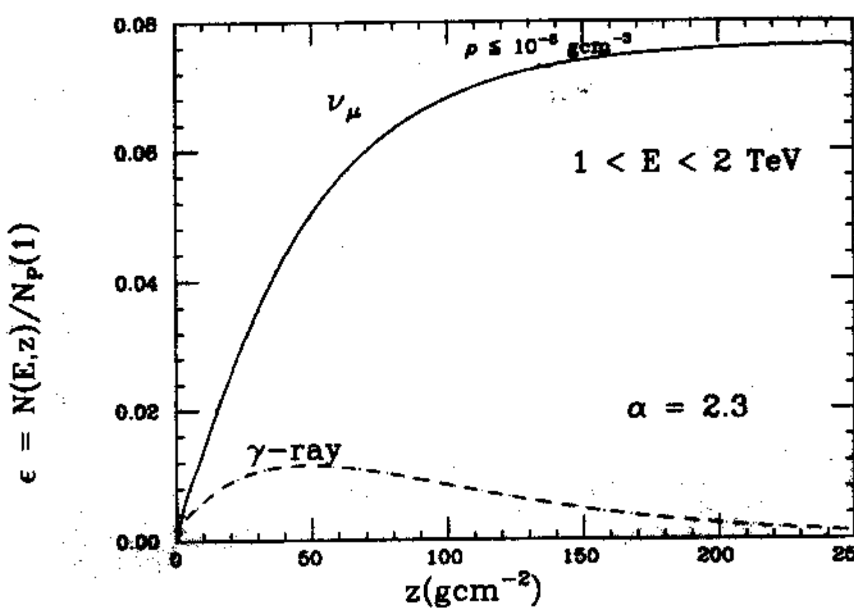

Fig. 1. The efficiency for muon neutrino (solid) and gamma ray (dashed) emission in the energy range $1 < E < 2$ TeV for a point source surrounded by a shell of matter density $\rho = 10^{-8}$ gcm^{-3}, as a function of the integrated path length z. The proton spectral index $\alpha = 2.3$. The gamma ray emission is independent of ρ over a reasonable range.

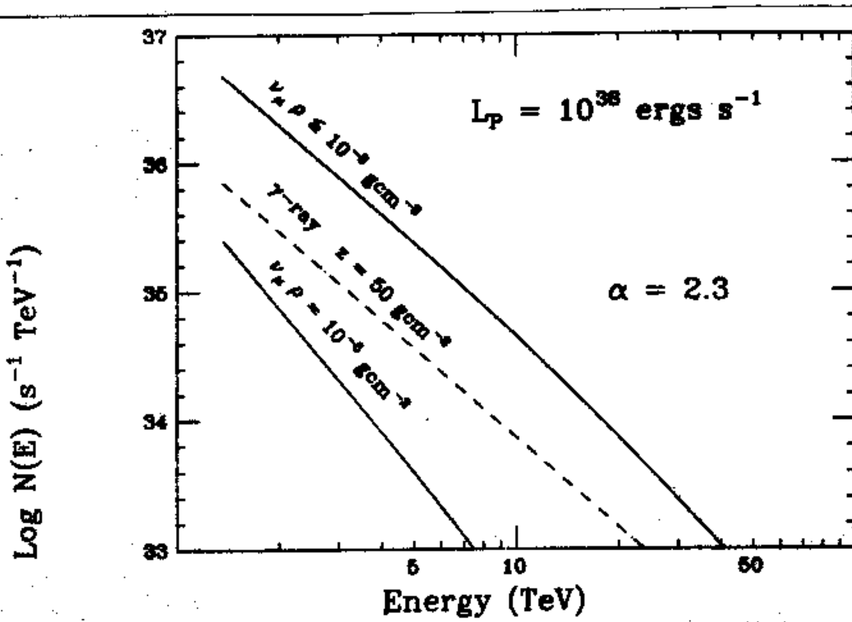

Fig. 2. The muon neutrino (solid) and gamma ray (dashed) emission spectra for a point source of proton luminosity 10^{38} erg s^{-1} surrounded by a shell of matter density ρ and integrated path length z. The proton spectral index $\alpha = 2.3$. The neutrino spectrum is shown for two values of ρ.

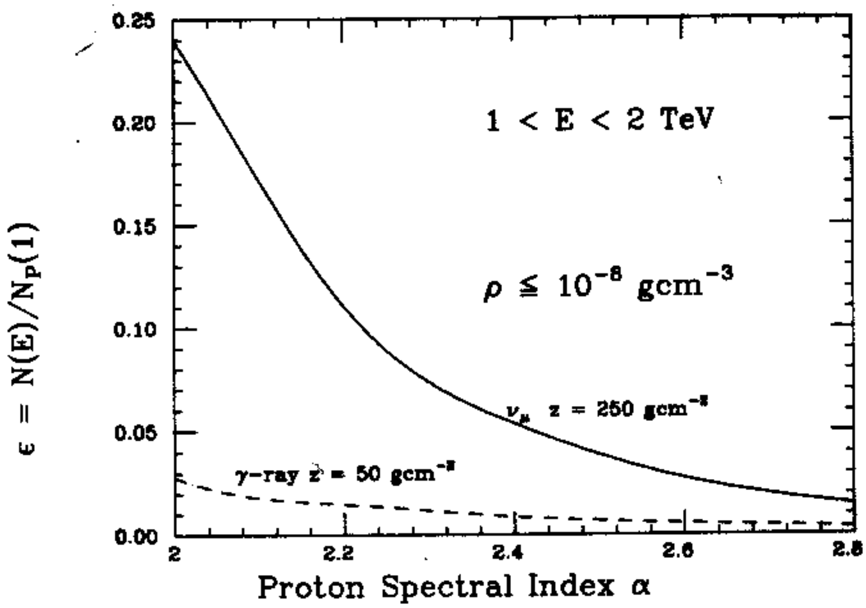

Fig. 3. The efficiency for muon neutrino and gamma ray emission in the energy range $1 < E < 2$ TeV for a point source surrounded by a shell of matter density ρ and column density z which are optimum in each case, as a function of the proton spectral index α.

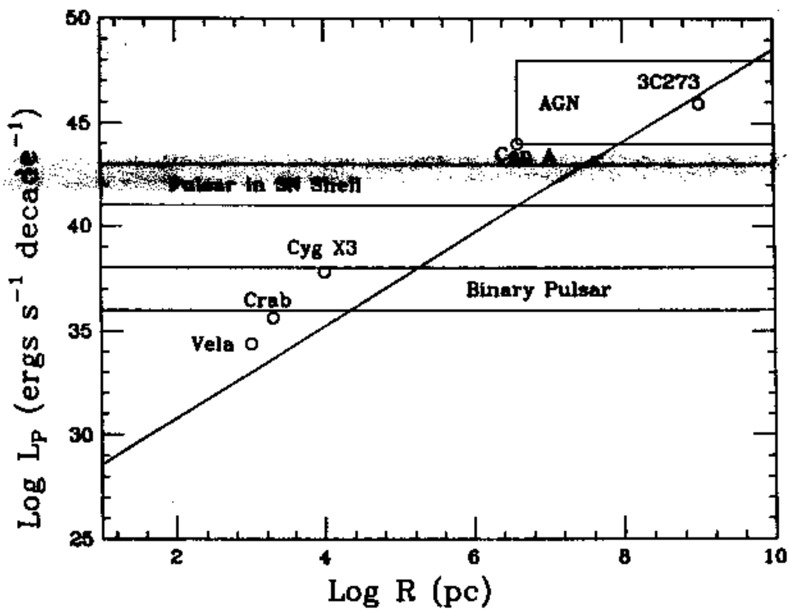

Fig. 4. The solid line shows the proton energy luminsity per decade required to produce detectable neutrinos or gamma rays under, optimum conditions for each, as a function of distance to the source. The points show the observed electromagnetic luminosities observed in x-ray and gamma ray bands for some specific sources inside and outside the galaxy.