High Energy Astrophysics

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The development of the atmospheric Cherenkov imaging technique has led to significant advances in γ-ray detection sensitivity in the energy range from 200 GeV to 50 TeV. The Whipple Observatory 10m reflector has detected the first galactic and extragalactic sources in the Northern Hemisphere; the Crab Nebula has been established as the standard candle for ground-based γ-ray astronomy. The highly variable Active Galactic Nuclei, Markarian 421 and Markarian 501, have proved to be particularly interesting. A new generation of telescopes with improved sensitivity has the promise of interesting measurements of fundamental phenomena in physics and astrophysics. VERITAS (the Very Energetic Radiation Imaging Telescope Array System) is one such next generation system; it is an array of seven large atmospheric Cherenkov telescopes planned for a site in southern Arizona.

I. THE RELATIVISTIC UNIVERSE

Our universe is dominated by objects emitting radiation via thermal processes. The blackbody spectrum dominates, be it from the microwave background, the sun or the accretion disks around neutron stars. This is the ordinary universe, in the sense that anything on an astronomical scale can be considered ordinary. It is tempting to think of the thermal universe as *THE UNIVERSE* and certainly it accounts for much of what we see. However to ignore the largely unseen, non-thermal, *relativistic*, universe is to miss a major component and one that is of particular interest to the physicist, particularly the particle physicist. The relativistic universe is pervasive but largely unnoticed and involves physical processes that are difficult to emulate in terrestrial laboratories.

The most obvious local manifestation of this relativistic universe is the cosmic radiation, whose origin, 86 years after its discovery, is still largely a mystery (although it is generally accepted, *but not proven*, that much of it arises in shock waves from galactic supernova explosions). The existence of a steady rain of particles, whose power law spectrum attests to their non-thermal origin and whose highest energies extend far beyond that achievable in man-made particle accelerators, attests to the strength and reach of the forces that power this strange relativistic radiation. If thermal processes dominate the "ordinary" universe, then truly relativistic processes illuminate the "extraordinary" universe and must be studied, not just for their contribution to the universe as a whole but as the denizens of unique cosmic laboratories where physics is demonstrated under conditions to which we can only extrapolate.

The observation of the extraordinary universe is difficult, not least because it is masked by the dominant thermal foreground. In places, we can see it directly such as in the relativistic jets emerging from AGNs but, even there, we must subtract the foreground of thermal radiation from the host elliptical galaxy. Polarization leads us to identify the processes that emit the radio, optical and X-ray radiation as synchrotron emission from relativistic particles, probably electrons, but polarization is not unique to B synchrotron radiation and the interpretation is not always unambiguous. The hard, power-law, spectrum of many of the non-thermal emission processes immediately suggests the use of the highest radiation detectors to probe such processes. Hence hard X-ray and γ-ray astronomical techniques must be the observational disciplines of choice for the exploration of the relativistic universe. Because the earth's atmosphere has the equivalent thickness of a meter of lead for this radiation, its exploitation had to await the development of space platforms for X-ray and γ-ray telescopes.

Although the primary purpose of the astronomy of hard photons is the search for new sources, be they point-like, extended or diffuse, it opens the door to the investigation of more obscure phenomenon in high energy astrophysics and even in cosmology and particle physics. Astronomy at energies up to 10 GeV has made dramatic progress since the launch of the Compton Gamma Ray Observatory in 1991 and that work has been summarized [1]. Beyond 10 GeV it is difficult to efficiently study γ-rays from space vehicles, both because of the sparse fluxes which necessitate large collection areas and the high energies which make containment a serious problem. The development of techniques whereby γ-rays of energy 100 GeV and above can be studied from the ground, using indirect, but sensitive, techniques is relatively new and has opened up a new area of high energy photon astronomy with some exciting possibilities and some preliminary results. The latter include the detection of TeV photons from supernova remnants and from the relativistic jets in AGNs. Such observations seriously constrain the models for such sources and in many cases lead to the development of a new paradigm. There remains the possibility that the annihilation lines from neutralinos might be discovered in the GeV-TeV region, that the evaporation of primordial black holes might be manifest by the emission of bursts of TeV photons, that the infrared density of intergalactic space might be probed by its absorbing effect on TeV photons from distant sources, and even (in some models) that the fundamental quantum gravity energy scale might be constrained by the observation of short-term TeV flares in extragalactic sources.

II. DETECTION TECHNIQUE

The techniques of ground-based Very High Energy (VHE) γ-ray astronomy are not new but only achieved credibility in the late eighties with the detection of the Crab Nebula. The most sensitive technique, the atmospheric Cherenkov imaging technique, is the one that has been most successful and is now in use at some eight observatories. Its history and present status has been reviewed elsewhere [2]. It is an optical "telescope" technique and thus suffers the usual limitations associated with optical astronomy: limited duty cycle, weather dependence, limited field of view. But it also has the advantage that it is relatively inexpensive because it uses the same detector technology (photomultipliers) as optical astronomy, the same optical reflectors that borrow from solar energy investigations, and the same pulse processing techniques that are routinely used in high energy particle physics. In addition the Cherenkov technique operates in an energy regime where the physics of particle interactions is relatively well understood and where there exist advanced Monte Carlo programs for the simulation of particle cascades.

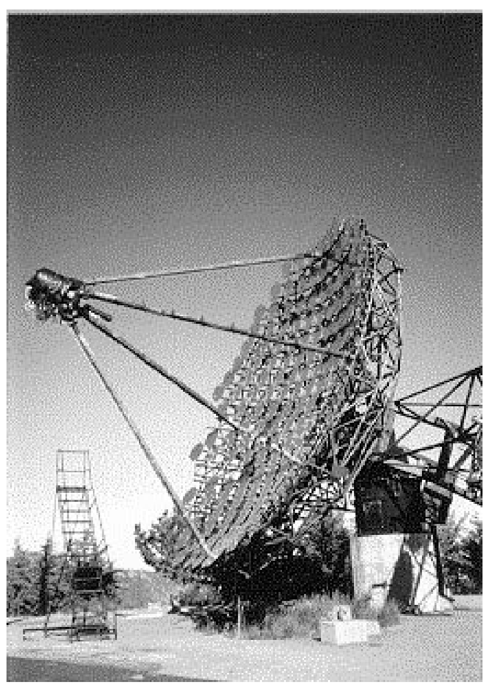

FIG. 1. The Whipple Observatory 10m reflector which will be the prototype for the telescopes in VERITAS.

In recent years, VHE γ-ray astronomy has been dominated by two advances in technique: the development of the atmospheric Cherenkov imaging technique, which led to the efficient rejection of the hadronic background, and the use of arrays of atmospheric Cherenkov telescopes to measure the energy spectra of γ-ray sources. The former is exemplified by the Whipple Observatory 10m telescope (Figure 1) with more modern versions CAT, the French telescope in the Pyrenees, and the Japanese-Australian CANGAROO telescope in Woomera, Australia. The most significant examples of the latter are the five telescope array of imaging telescopes on La Palma in the Canary Islands which is run by the Armenian-German-Spanish collaboration, HEGRA, and the four, soon to be seven, Telescope Array in Utah which is operated by a group of Japanese institutions. These techniques are relatively mature and the results from observations with overlapping telescopes are in good agreement. Vigorous observing programs are now in progress at all of these facilities; the vital observing threshold has been achieved whereby both galactic and extragalactic sources have been reliably detected. Many exciting results are anticipated as more of the sky is observed with this generation of telescopes.

III. GALACTIC SOURCES

It is a measure of the maturity of this new discipline that the existence and study of galactic sources of TeV radiation is now considered ordinary and relatively uncontroversial. This is a dramatic change from only a decade ago when the existence of any galactic sources at all was hotly contested. These sources were always variable and difficult to confirm or refute [4]; it was not until the observation of steady sources, in particular, the observation of the Crab Nebula (which has become the standard candle), that the relative sensitivity of the different techniques could be assessed and some standards of credibility set.

The Crab Nebula has been observed by some eight independent groups and no evidence for variability has been detected. It has been seen at energies from 200 GeV to more than 50 TeV and accurate energy spectra have been determined [3]. Originally predicted by Gould [5] as a TeV energy source based on a Compton-synchrotron model, the complete γ-ray spectrum can now be fitted by an updated version of the same model [3]. The variable parameter in this model is the magnetic field which is set by the TeV observations at 16 ± 1 nanotesla, somewhat smaller than the value estimated from the equipartition of energy. In practice, recent optical observations reveal a complex structure at the center of the nebula (where the TeV photons are believed to originate) and more sophisticated models are certainly called for.

VHE γ-rays have also been detected from other galactic sources. All of these detections are of sources with negative declinations, best seen in the Southern Hemisphere where there are fewer VHE observatories and hence the detections have largely been by one group. The exception is the γ-ray pulsar PSR1706-44 which was discovered by the CANGAROO group [6] and confirmed by the Durham group [7]; both of these groups operate from Australia. The source is detected by EGRET at MeV-GeV energies as 100% pulsed. There is no evidence in the TeV signal for pulsations but there is weak evidence that the pulsar is in a plerion which may be the source of the TeV γ-rays. The CANGAROO group also report the detection of an unpulsed TeV signal from a location close to the Vela pulsar [8]; the position coincides with the birthplace of the pulsar and hence the signal may originate in a weak plerion left after the ejection of the pulsar. Another interesting result is the detection of Cen X-3 by the Durham group [9].

Perhaps the most surprising (and controversial) result is the detection of a TeV source that is coincident with one part of the shell of the supernova remnant, SN1006 [10]. X-ray observations had shown that there is non-thermal emission from two parts of the shell that is consistent with synchrotron emission from electrons with energy up to 100 TeV; hence the TeV γ-ray detection is not a surprise. The TeV emission is consistent with inverse Compton emission from electrons which have been shock accelerated in the shell. However it is not clear why it should be seen from only one region. Because this represents the first direct detection of SNR shell emission this result, when confirmed, has great significance. Not only can the magnetic field be estimated but also the acceleration time; these two parameters are very important for shock acceleration theory. More sensitive observations may reveal the detailed energy spectrum, whether or not the source is extended, and the relative strength of the TeV emission from each shell.

Ideally, of course, one would like to see direct evidence from VHE γ-ray astronomy of emission from hadron collisions in SNR shells. These SNRs are widely believed to be the source of the hadronic cosmic rays seen in the solar system (at least up to proton energies of 100 TeV) which fill the galaxy. However this canonical model mostly rests on circumstantial evidence and it is highly desirable to find the smoking gun that would clinch the issue. Supernovae certainly have sufficient energy and their occurrence rate is about right; also there is a known mechanism associated with shock fronts to explain acceleration. Hence when EGRET detected a small number of γ-ray sources at GeV energies which appeared to coincide with known SNRs [11], it was widely believed that the cosmic ray origin problem had been solved. However Drury et al. [12] had shown that the γ-ray spectrum of such sources should be rather flat power-laws that would extend to TeV energies. Extensive observations by the Whipple collaboration have failed to find any evidence for TeV emission [13]. The upper limits are shown in Figure 2 along with the EGRET points. More elaborate models have been constructed that can be made to fit the observations [14]. It is also possible that the EGRET source/SNR identifications are in error since the sources are not strong and the galactic γ-ray plane is a confused region at MeV/GeV energies. Either way, it would be reassuring for theories of cosmic ray origins to see definite detections from some shell-type SNRs where the emission is consistent with π production in the shell. The next generation of VHE detectors should provide these definitive observations.

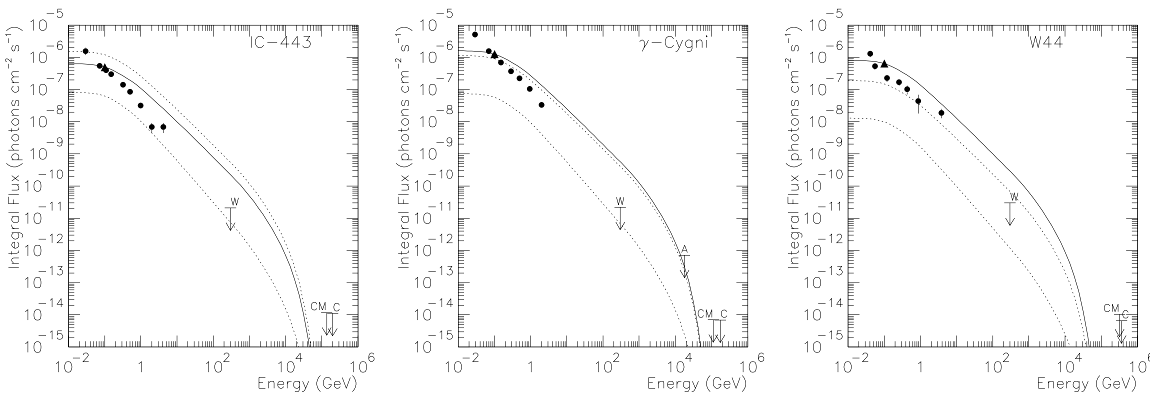

FIG. 2. Whipple Observatory flux upper limits (indicated by W) for shell-type SNRs. The lower energy points are from EGRET. The solid curves are extrapolations from the EGRET integral fluxes for γ-rays arising from π^o decay. Upper limits from air shower arrays are also shown.

IV. EXTRAGALACTIC SOURCES

A. Relativistic Jets

One of the most surprising results to come from VHE γ-ray astronomy has been the discovery of TeV-emitting blazars. Unlike the observation of galactic supernovae such as the Crab Nebula, which are essentially standard candles, the light-curves of blazars are highly variable. In Figure 3 the nightly averages of the TeV flux from Markarian 421 (Mkn 421) in 1995 are shown as observed at the Whipple Observatory [15]. Although AGN variability was a feature of the AGNs observed by EGRET on the Compton Gamma Ray Observatory at energies from 30 MeV to 10 GeV, the weaker signals (because of the finite collection area) do not allow such detailed monitoring, particularly on short time-scales.

Active galactic nuclei (AGN) are the most energetic on-going phenomena that we see in extragalactic astronomy. The canonical model of these objects is that they contain massive black holes (often at the center of elliptical galaxies) surrounded by accretion disks and that relativistic jets emerge perpendicular to the disks; these jets are often the most prominent observational feature. Blazars are an important sub-class of AGNs because they seem to represent those AGNs which have one of their jets aligned in our direction. Observations of such objects are therefore unique.

The VHE γ-ray astronomer is thus in the position of the particle physicist who is offered the opportunity to observe the accelerator beam, either head-on or from the side. For the obvious reason that there is more energy transferred in the forward direction the particle physicist usually chooses to put his most important detectors directly in the direction of the beam (or close to it) and its high energy products. While such observations give the best insight into the energetic processes in the jet, they do not give the best pictorial representation. Hence just as it is difficult to visualize the working of a cannon by looking down its barrel, it is difficult to get a picture of the jet by looking at it

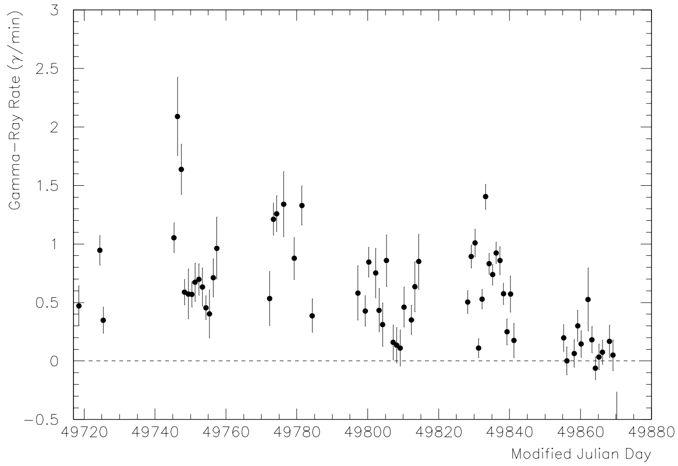

FIG. 3. Daily VHE γ-ray count rates for Mkn 421 during 1995 (from [15]).

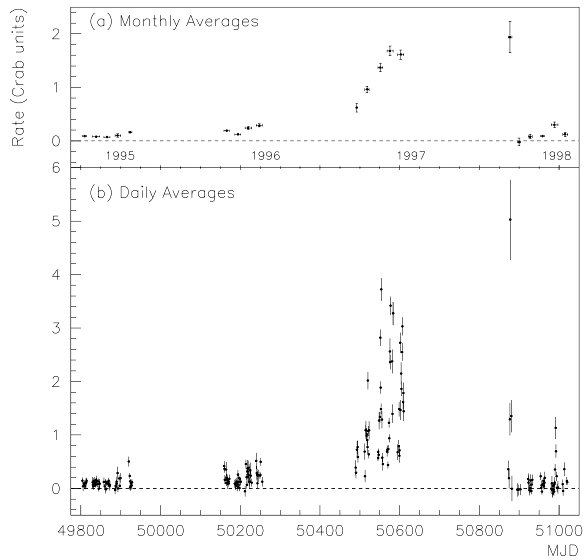

FIG. 4. Average monthly (a) and daily (b) VHE γ-ray flux (in units of VHE Crab flux) for Mkn 501 between 1995 and 1998 (from [26]).

head-on. Observations at right angles to the jet give us our best low energy view of the jet phenomenon and indeed provide us with the spectacular optical pictures of jets from nearby AGNs (such as M87).

B. Sources

Mkn 421 is the closest example of an AGN which is pointing in our direction. It is a BL Lac object, a sub-class of blazars, so-called because they resemble the AGN, BL Lacertae which is notorious because of the lack of emission lines in its optical spectrum. Because such objects are difficult, and somewhat uninteresting, for the optical astronomer they were largely ignored until they were found to be also strong and variable sources of X-rays and γ-rays. Mkn 421 achieved some notoriety largely because it was the first extragalactic source to be identified as a TeV γ-ray emitter [16]. At discovery, its average VHE flux was $\approx$ 30% of the VHE flux from the Crab Nebula. Markarian 501 (Mkn 501), which is similar to Mkn 421 in many ways, was detected as a VHE source by the Whipple group in May 1995 [17]. It was only 8% of the level of the Crab Nebula and was near the limit of detectibility of the technique at that time. The discovery was made as part of an organized campaign to observe objects that were similar to Mkn 421 and were at small redshifts. This same campaign later yielded the detection of the BL Lac object, 1ES 2344+514 [18] which is also close (z = 0.044). Recently the Durham group has announced the detection of the BL Lac object, PKS2155-304 [19] which is also at a small redshift (z = 0.116).

TABLE I. Properties of the VHE BL Lac objects

Object	z	EGRET flux[a] (E>100 MeV) (10^{-7}cm^{-2}s^{-1})	Average flux (E>300 GeV) (10^{-12}cm^{-2}s^{-1})	M_v [a]	$\mathcal{F}_X$ [a] (2 keV) (μJy)	$\mathcal{F}_R$ [a] (5 GHz) (mJy)
Mkn 421	0.031	1.4±0.2	40	14.4	3.9	720
Mkn 501	0.034	3.2±1.3	≥8.1	14.4	3.7	1370
1ES 2344+514	0.044	<0.7	≤8.2	15.5	1.1	220
PKS 2155-304	0.116	3.2±0.8	42	13.5	5.7	310
3C 66A	0.444	2.0±0.3	30[b]	15.5	0.6	806

[a] Radio, optical, and X-ray data from [21]. EGRET data from D.J. Thompson (priv. comm.), [22], and [23].
[b] 1 TeV flux value.

A more controversial, but potentially more important detection, is that of 3C 66A reported by the Crimean group [20]. These sources are summarized in Table I. Whereas the first two sources have been seen by a number of groups, the last three are reported by only one group and require confirmation.

C. Variability

Perhaps the most exciting aspect of these detections is the observation of variability on time-scales from minutes to hours. The very large collection areas ($> 10,000 m^2$) associated with atmospheric Cherenkov Telescopes is ideally suited for the investigation of short term variability. The VHE emission from the two best observed sources, Mkn 421 and Mkn 501 (Figure 4), varies by a factor of a hundred. Although many hundreds of hours have now been devoted to their study, the variations are so complex that it is still difficult to characterize their emissions. It has been suggested [15] that for Mkn 421 the emission is consistent with a series of short flares above a baseline that falls below the threshold of the Whipple telescope (Figure 3); the average flare duration is one day or shorter.

The most important observations of Mkn 421 were in May, 1996 when it was found to be unusually active. On May 7, a flare was observed with the largest flux ever recorded from a VHE source. The observations began when the flux was already several times that of the Crab Nebula and it continued to rise over the next two hours before levelling off (Fig. 5). Observations were terminated as the moon rose but the following night it was observed at its quiescent level. One week later (May 15) a smaller, but shorter, flare was detected; in this case the complete flare was observed and the doubling time in the rise and fall was $\approx$ 15 minutes. This is the shortest time variation seen in any extragalactic γ-ray source at energies $>$ 10 MeV (apart from in a γ-ray burst).

Mkn 501 is also variable, but as at other wavelengths, the characteristic time seems longer. Its baseline emission has varied by a factor of 15 over four years [26] (Figure 4). Hour-scale variability has also been detected but its most important time variation characteristic appears to be the slow variations seen over the five months in 1997.

D. Spectrum

The atmospheric Cherenkov signal is essentially calorimetric and hence it should be possible to derive the γ-ray energy spectrum from the observed light pulse spectrum. In practice it is more difficult because, unless an array of detectors is used, the distance to the shower core (impact parameter) is unknown. Although the extraction of a spectrum from even a steady and relatively steady source as the Crab Nebula required considerable effort and the development of new techniques, it was relatively easy to measure the spectra of Mkn 421 and Mkn 501 in their high state because the signal was so strong. The general features of the spectra derived from the Whipple observations are in agreement with those derived at the HEGRA telescopes [28].

The May 7, 1996 flare of Mkn 421 provided an excellent data base for the extraction of a spectrum; the data can be fit by a simple power-law ($dN/dE \propto E^{-2.6}$). There is no evidence of a cutoff up to energies of 5 TeV [24] (Figure 6). Because of the possibility of a high energy cutoff due to intergalactic absorption there is considerable interest in the highest energy end of the spectrum. Large zenith angle observations at Whipple [27] and observation by HEGRA [28] confirm the absence of a cutoff out to 10 TeV.

The generally high state of Mkn 501 throughout 1997 give data from the Whipple telescope that can be best fit by a curved spectrum of the form: dN/dE and $E^{-2.20-0.45 log_{10} E}$ [29] (Figure 6). Here the spectrum extends to at least 10 TeV. The curvature in the spectrum could be caused by the intrinsic emission mechanism or by absorption in the source. Since Mkn 421 and Mkn 501 are virtually at the same redshift it is unlikely that it could be due to intergalactic absorption since Mkn 421 does not show any curvature [30].

E. Multiwavelength Observations

The astrophysics of the γ-ray emission from the jets of AGNs are best explored using multiwavelength observations. These are difficult to organize and execute because of the different observing constraints on radio, optical, X-ray,

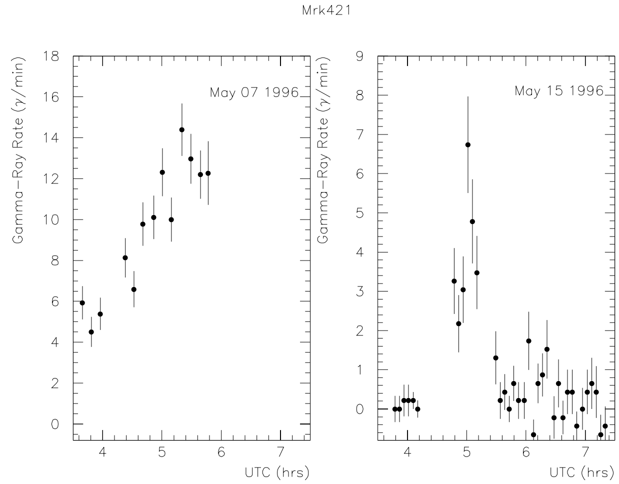

FIG. 5. Mkn 421 flares of 1996 May 7 (left) and May 15 (right) (adapted from [25]).

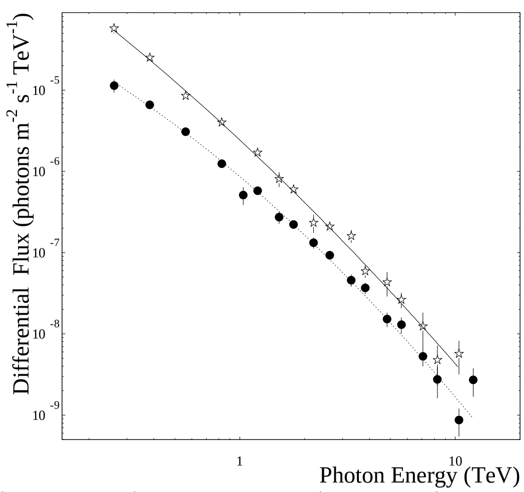

FIG. 6. VHE spectra of Mkn 421 (filled circles) and Mkn 501 (open stars) as measured with the Whipple Observatory telescope [30].

space-based γ-ray and ground-based γ-ray observatories. Of necessity observations are often incomplete and, when complete coverage is arranged, the source does not always cooperate by behaving in an interesting way!

The first multiwavelength campaign on Mkn 421 coincided with a TeV flare on May 14-15, 1994 and showed some evidence for correlation with the X-ray band; however no enhanced activity was seen in EGRET [31]. A year later, in a longer campaign, there was again correlation between the TeV flare and the soft X-ray and UV data but with an apparent time lag of the latter by one day [15] (Figure 7). The variability amplitude is comparable in the X-ray and TeV emission ($\approx$ 400%) but is smaller in the EUV ($\approx$200%) and optical ($\approx$20%) bands. In April, 1998 there was again a correlation seen between an X-ray flare observed by SAX and Whipple; in this case the TeV flare was much shorter (a few hours) compared to the X-ray (a day) [32].

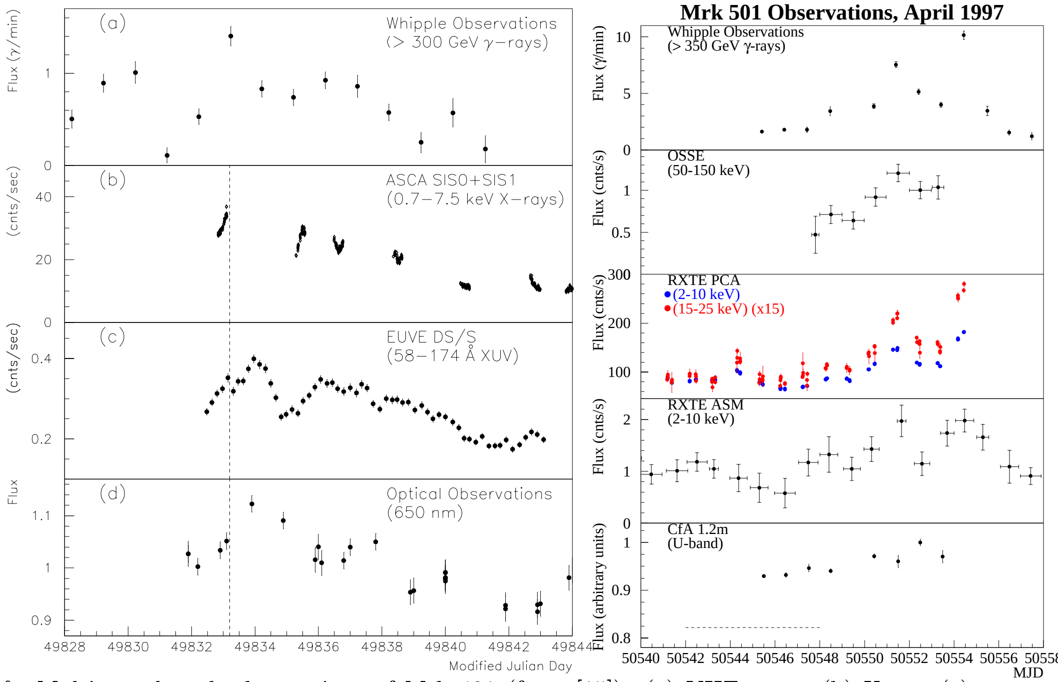

FIG. 7. *Left*: Multi-wavelength observations of Mrk 421 (from [15]): (a) VHE γ-ray, (b) X-ray, (c) extreme UV, and (d) optical lightcurves taken during the period 1995 April-May (April 26 corresponds to MJD 49833). *Right:* Multi-wavelength observations of Mkn 501 (adapted from [33]): (a) γ-ray, (b) hard X-ray, (c) soft X-ray, (d) U-band optical taken during the period 1997 April 2-20 (April 2 corresponds to MJD 50540). The dashed line in (d) indicates the optical flux in 1997 March.

The first multiwavelength campaign on Mkn501 was undertaken when the TeV signal was seen to be at a high level. The surprising result was that the source was detected by the OSSE experiment on CGRO in the 50-150 kev band (Figure 7). This was the highest flux ever recorded by OSSE from any blazar (it has not detected Mkn 421) but the amplitude of the X-ray variations (≈200%) was less than those of the TeV γ-rays (≈400%) [33].

F. Multiwavelength Power Spectra

Because of the strong variability in the TeV blazars it is difficult to represent their multiwavelength spectra. In Figure 8 we show the fluxes plotted as power ($\nu \times F_\nu$) from Mkn 421 and Mkn 501 during flaring as well as the average fluxes. Both sources display the two peak distribution characteristic of Compton-synchrotron models, e.g., the Crab Nebula. Whereas the synchrotron peak in Mkn 421 occurs near 1 keV, that of Mkn 501 occurs beyond 100 keV which is the highest seen from any AGN. In 1998 the synchrotron spectrum peak in Mkn 501 shifted back to 5 keV and the TeV flux fell below the X-ray flux.

G. Implications

The sample of VHE emitting AGNs is still very small but it is possible to draw some conclusions from their properties (summarized in Table I).

- The first three objects, all detected by the Whipple group, are the three closest BL Lacs in the northern sky. Some 20 other BL Lacs have been observed with z < 0.10 without detectable emission. This could be fortuitous, because they are standard candles and these are closest (but the distance differences are small), or because they suffer the least absorption (but there is no cutoff apparent in their spectra).

- All of the objects are BL Lacs; because such objects do not show emission lines and therefore probably do not have strong optical/infrared absorption close to the source, it is suggested that BL Lacs are preferentially VHE emitters.

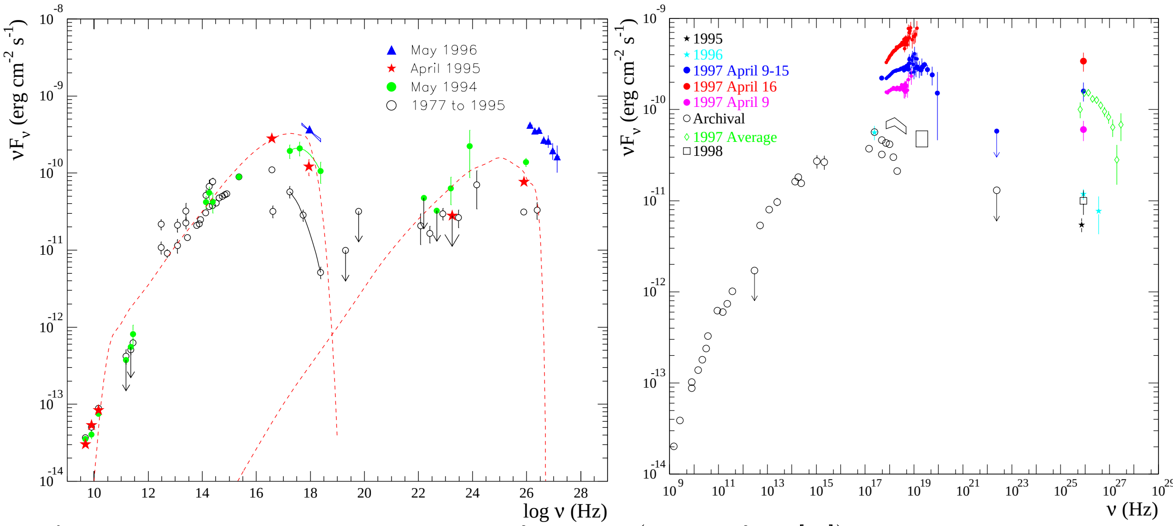

FIG. 8. *Left:* The multi-wavelength power spectrum of Mkn 421 (adapted from [15]). The dashed line shows an SSC model fit to the data. *Right:* The multi-wavelength power spectrum of Mkn 501 (adapted from [33]).

- Four of the five sources are classified as XBLs which indicates that they are strong in the X-ray region and that the synchrotron spectrum most likely peaks in that range (and that the Compton spectrum peaks in the VHE γ-ray range). The fifth, 3C 66A, is an RBL, like many of the blazars detected by EGRET; it is believed that these blazars have synchrotron spectra that peak at lower energies and Compton spectra that peak in the HE γ-ray region.

- Only three (Mkn 421, PKS 2155-304 and 3C 66A) are listed in the Third EGRET Catalog; there is a weak detection reported by EGRET for Mkn 501.

- If 3C 66A is confirmed (and to a lesser extent PKS 2155-305), then the intergalactic absorption is significantly less than had been suggested from galactic evolution models.

- There is evidence for variability in all of the sources. The rapid variability seen in Mkn 421 indicates that the emitting region is very small which might suggest it is close to the black hole. In that case the local absorption must be very low (low photon densities). It seems more likely that the region is well outside the dense core.

There are three basic classes of model considered to explain the high energy properties of BL Lac jets: Synchrotron Self Compton (SSC), Synchrotron External Compton (SEC) and Proton Cascade (PC) Models. In the first two the progenitor particles are electrons, in the third they are protons. VHE γ-ray observations have constrained the types of models that are likely to produce the γ-ray emission but still do not allow any of them to be eliminated. For instance, the correlation of the X-ray and the VHE flares is consistent with the first two models where the same population of electrons radiate the X-rays and γ-rays. There is little evidence for the IR component in BL Lac objects which would be necessary in the SEC models as the targets for Compton-scattering, so this particular type of model may not be likely for these objects. The PC models which produce the γ-ray emission through e^+e^- cascades also have great difficulty explaining the rapid cooling observed in the TeV emission from Mkn 421. Also the high densities of unbeamed photons near the nucleus, such as the accretion disk or the broad line region, are required to initiate the cascades and these cause high pair opacities to TeV γ-rays [34].

Significant information comes from the multiwavelength campaigns (although thus far these have been confined to Mkn 421 and Mkn 501). Simultaneous measurements constrain the magnetic field strength (B) and Doppler factor

(δ) of the jet when the electron cooling is assumed to be via synchrotron losses. The correlation between the VHE γ-rays and optical/UV photons observed in 1995 from Mkn 421 indicates both sets of photons are produced in the same region of the jet; $\delta \gtrsim 5$ is required for the VHE photons to escape significant pair-production losses [15]. If the VHE γ-rays are produced in the synchrotron-self-Compton process, $\delta = 15 - 40$ and $B = 0.03 - 0.9$G for Mrk 421 [35], [36] and $\delta < 15$ and $B = 0.08 - 0.2$G for Mkn 501 [29], [36]. On the other hand by assuming protons produce the γ-rays in Mkn 421, Mannheim [37] derives $\delta = 16$ and $B = 90$G. The Mkn 421 values of δ and B are extreme for blazars, but they are still within allowable ranges and are consistent with the extreme variability of Mkn 421.

V. INTERGALACTIC ABSORPTION

Thus far it has not been possible to make a direct measurement of the infrared background radiation at wavelengths more than 3.5 microns and less than 140 microns. This is unfortunate since the background potentially contains valuable information for cosmology, galaxy formation and particle physics. The problem for direct measurement is the presence of foreground local and galactic sources. However the infrared background can make its presence felt by the absorption it produces on the spectra of VHE γ-ray sources when they are at great distances. The absorption is via the $\gamma\gamma \rightarrow e^+e^-$ process, the physics of which is well understood. The maximum absorption occurs when the product of the energy of the two photons (γ-ray and infrared) is approximately equal to the product of the rest masses of the electron-pair. Hence a 1 TeV γ-ray is most heavily absorbed by 0.1eV (1.2 micron) infrared photon in head-on collisions.

The importance of this effect for VHE and UHE γ-ray astronomy was first pointed out by Nikishov [38]; its potential for making an indirect measurement of the infrared background was pointed out by Gould and Schreder [39] and, more recently, in the aftermath of the EGRET detections of AGNs, by Stecker and de Jager [40]. At the redshift of the AGNs detected at VHE energies to date (0.03 to 0.5) if the infrared density has the value assumed in some models [40], the effect is appreciable and should be apparent in carefully measured energy spectra in the range 1 to 50 TeV.

Ideally for such a measurement the intrinsic emission spectrum of the γ-rays from the distant source should be known. In practice this is not the case although thus far all the AGNs detected in the GeV-TeV range appear to have very smooth power-law spectra. Biller et al. [41] have made a conservative derivation of upper limits on the infrared spectrum based on the measured γ-ray spectrum from 0.5 to 10 TeV from Mkn 421 and Mkn 501 by the Whipple and HEGRA groups. These upper limits apply to infrared energies from 0.025 to 1.0 eV; they are the best upper limits over this range. At some wavelengths, these limits are as much as an order of magnitude below the upper limits set by the DIRBE/COBE satellite (see Figure 9).

The infrared densities are calculated such that they do not cause the shape of the observed VHE spectrum to deviate from the bounds set from the VHE measurements. This approach has the effect of anchoring the lower energy TeV data to the appropriate infrared upper limits and then extending these bounds so that they are consistent with those based on the shape and extent of the AGN spectra at the higher energies. Thus the maximum energy density in each interval of infrared energy is determined; these limits are plotted in Figure 9 where a maximum energy of 10 TeV is considered; also shown are the upper limits from other methods.

These upper limits do not conflict with the predictions of the infrared background based on detailed models of galactic evolution [42]. They do however allow some more cosmological possibilities to be eliminated. In particular in one scenario, density fluctuations in the early universe ($z \approx 1000$) could have produced very massive objects which would collapse to black holes at later times and could explain the dark matter. However although undetectable now, they would have produced an amount of infrared radiation that would have exceeded the above limits [41]. These limits also place some constraints on radiative neutrino decay.

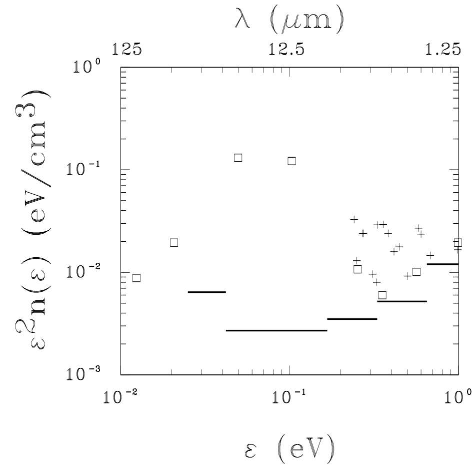

FIG. 9. Upper limits to the background IR density. The solid lines show the limits derived assuming the VHE spectra of Mkn 421 and Mkn 501 extend to 10 TeV and the dashed lines show the limits if the spectra extend only to 6 TeV. Other symbols represent upper limits from direct measurements (squares are from COBE/DIRBE measurements). Figure from ([41]).

VI. GAMMA RAY BURSTS

The contribution of TeV observations to the physics of γ-ray bursts is at once the most speculative and most important (potentially) of all the scientific topics considered here. As yet, there is no positive detection of TeV photons during or immediately after a classical γ-ray burst (GRB) (although there is one tantalizing but unconfirmed observation [43]). However since there is no turn over seen in the spectra of GRBs detected by EGRET at energies > 30 GeV, there is the potential for interesting observations at VHE energies. The observed EGRET spectra are power laws with differential indices 1.95 ± 0.25 [44]. The sensitivity of current ACTs is such that sources with spectral indices ≈ 2 would be easily detectable even for fluences as low as 5×10^{-8} ergs/cm^2 [45]. Although only four of the very bright BATSE bursts were seen by EGRET, these were the brightest to occur within the field of view of EGRET and there is nothing to suggest that all bursts might not have GeV-TeV components. In fact, EGRET was not a very sensitive detector for GRBs both because of its limited collection area and its deadtime. There are now several models that suggest that TeV emission may be a strong feature of GRBs [47], [48].

There are however several negative factors concerning the possible detection of GRBs by ACTs. The narrow field of view combined with the low duty-cycle (clear, dark nights) lessens the chance of the serendipitous detection of the TeV component of a GRB. If the GRBs are truly cosmological (as they appear to be), then intergalactic absorption by pair production on infra-red photons must come into play at some point, steepening the apparent spectra. However the next generation of ACTs will have reduced energy thresholds, better flux sensitivities and rapid slew capabilities; these features combined with the more accurate source locations anticipated with the launch of HETE-2 may provide TeV detections at the rate of a few per year. In addition, the water Cherenkov detector, MILAGRO, will have all sky coverage (although reduced sensitivity below 1 TeV) and will have guaranteed coverage of some bursts detected by satellites.

A feature of the EGRET GRB observations was that there was evidence for delayed emission (up to 1.5 hours) from the burst site [46]. This may indicate a different component at these energies. Some models [47] predict that this delayed emission could persist for days and could hence be easily observed with narrow field of view instruments.

The detection of a TeV γ-ray component in a GRB would be a serious parameter for the emission models, in particular the Lorentz bulk motion in the source would be constrained. It would also be an independent distance indicator since the source would have to show absorption if the redshift was > 0.1.

VII. NEUTRALINOS

The best candidate for the cold dark matter component is the neutralino, the lightest supersymmetric particle. These particles annihilate with the emission of a single γ-ray line whose energy is equal to that of the neutralino mass; however other annihilation modes are possible and there may be a γ-ray continuum. There are limits on the possible masses from cosmology and from accelerator experiments but the range from 30 GeV to 3 TeV is allowed. The upper part of this range would be accessible for study by ground-based γ-ray telescopes. The neutralinos, if they exist, would be expected to cluster to the center of galaxies and might be detectable by their γ-ray emission, either as a line or a continuum. Detailed numerical simulations indicate that there may be a strong density enhancement towards the centers of galaxies such as our own. Hence the Galactic Center is a prime candidate for observations. This hypothesis is given some credence by the detection of a somewhat extended γ-ray source at the Galactic Center [49] at energies above 300 MeV.

In a recent paper, Bergstrom, Ullio and Buckley [51] have estimated the flux from the annihilation radiation of neutrinos in the Galactic Center using the most recent models of the galactic mass distribution. The predicted line has a relative width of 10^{-3}. Neither space nor ground-based detectors have energy resolution of this quality (even in the next generation of detectors) but the intensity of the line is such that it might be detectable even with relatively crude energy resolution.

VIII. QUANTUM GRAVITY

Some quantum gravity models predict the refractive index of light in vacuum to be dependent on the energy of the photon. This effect, originating from the polarization of space-time, causes an energy- dependance to the velocity of light. Effectively, the quantum fluctuations are on distance scales near the Planck length, ($L_P \simeq 10^{-33}$cm), (corresponding to time-scales of $1/E_P$, the Planck mass ($\simeq 10^{19}$GeV)). Different models of quantum gravity give widely B differing predictions for the amount of time dispersion. In one model the first order time dispersion is given by:

$$\Delta t \simeq \xi \frac{E}{E_{QG}} \frac{L}{c} \tag{1}$$

where Δt is the time delay relative to propagation at the velocity of light, c, ξ is a model-dependent factor of order 1, E is the energy of the observed photons, E_{QG} is the quantum energy scale, and L is the distance from the source. In most models $E_{QG} \approx E_P$ but, in recent work in the context of string theory, it can be as low as 10^{16}GeV [52].

Recently it has been suggested that astrophysical observations of transient high energy emission from distant sources might be used to measure (or limit) the quantum gravity energy scale. Amelino-Camelia et al. [53] suggested that BATSE observations of GRBs would provide a powerful method of probing this fundamental constant if variations on time-scales of milliseconds could be measured in the MeV signal in a GRB which was measured to be at a cosmological distance. Such time-scales and distances have been measured in GRBs but so far not in the same GRB. The absence of time dispersion in flares of TeV γ-rays from AGNs at known distances provides an even more sensitive measure. Biller et al. [54] have used the sub-structure observed in the 15 minute flare in Mkn 421 observed by the Whipple group on April 15, 1996 [25] to derive a lower limit on E_{QG}.

On a time-scale of 280 seconds there is weak (2σ) evidence for correlated variability in two energy ranges: 300 GeV to 2 TeV and > 2 TeV. For a Hubble Constant of 85 km/s/Mpc, the distance L is 1.1×10^{16} light-seconds. This gives a lower limit to E_{QG} of $> 4 \times 10^{16}$GeV assuming ξ is ≈ 1. This is the most convincing lower limit on E_{QG} to date.

Because VHE γ-ray astronomy is still in its infancy and the exposure time on AGNs still limited, it is likely that much more sensitive measurements will lead to better limits on E_{QG} as a new generation of detectors comes on-line and permits the detection of shorter time-variations and/or more distant sources.

IX. FUTURE PROSPECTS

It is clear that to fully exploit the potential of ground-based γ-ray astronomy the detection techniques must be improved. This will happen by extending the energy coverage of the technique and by increasing its flux sensitivity. Ideally one would like to do both but in practice there must be trade-offs. Reduced energy threshold can be achieved by the use of larger but cruder mirrors and this approach is currently being exploited using existing arrays of solar heliostats (STACEE and CELESTE). A German-Spanish project (MAGIC) to build a 17m aperture telescope using state-of-the-art technology has also been proposed. These projects may achieve thresholds as low as 20-30 GeV where they will effectively close the current gap in the γ-ray spectrum from 20 to 200 GeV. Ultimately this gap will be covered by GLAST, the next generation γ-ray space telescope (which will use solid-state detectors) which is scheduled for launch in 2005 by an international collaboration. Extension to even higher energies can be achieved by the atmospheric Cherenkov telescopes working at large zenith angles and by particle arrays at very high mountain altitudes. An interesting telescope that will soon come on line and will complement these techniques is the MILAGRO water Cherenkov detector in New Mexico which will operate 24 hours a day with wide field of view and will have good sensitivity to γ-ray bursts and transients.

VERITAS, with seven 10 m telescopes arranged in a hexagonal pattern with 80 m spacing, will aim for the middle ground, with its primary objective being high sensitivity in the 100 GeV to 10 TeV range. It will be located in southern Arizona and will be the logical development of the Whipple telescope. It is hoped to begin construction in 1999 and to complete the array by 2004.

The German-French HESS (initially four, and eventually perhaps sixteen, 10m class telescopes) will be built in Namibia and the Japanese NEW CANGAROO array (with three to four telescopes in Australia) will have similar objectives. In each case the arrays will exploit the high sensitivity of the imaging ACT and the high selectivity of the array approach. The relative flux sensitivities of the present and next generation of VHE telescopes as a function of energy are shown in Figure 10, where the sensitivities of the wide field detectors are for one year and for the ACT for 50 hours; in all cases a 5σ point source detection is required. The VERITAS sensitivity is derived from Monte Carlo simulations using the Whipple telescope as a baseline [55]. The projected sensitivities of MAGIC, HESS, New CANGAROO and VERITAS are somewhat similar and we will refer to them collectively as Next Generation Gamma Ray Telescopes (NGGRTs).

It is apparent from this figure that on the low energy side, the NGGRTs such as VERITAS will complement the GLAST mission (launch date 2005) and will overlap with STACEE and CELESTE which will be coming on line in 1999. At its highest energy, they will overlap with the Tibet Air Shower Array. It will cover the same energy range as MILAGRO but with greater flux sensitivity; however the wide field coverage of MILAGRO will permit the detection of transient sources which, once detected, can be monitored by VERITAS. As a Northern Hemisphere telescope VERITAS will complement the coverage of neutrino sources discovered by AMANDA and ICE CUBE at the South Pole. Finally if the sources of ultra-high energy cosmic rays discovered by HiRes and Auger are localized to a few degrees, VERITAS will be the most powerful instrument for their further localization and identification.

A. Science to come

a. AGNs By measuring the high energy end of the spectra for several EGRET sources. The NGGRTs can help determine what particles produce the γ-ray emission in blazars (electrons should show cut-offs which correlate with lower energy spectra, protons would not show a simple correlation). In addition, the recent efforts [65] to unify the different classes of blazar into different manifestations of the same object type can be tested. In addition the infrared background will be probed by the detection of sources over a range of redshifts.

b. SNRs The existing data clearly indicate that in order to resolve the contributions of the various γ-ray emission mechanisms, one needs more accurate measurements over a more complete range of energies. The NGGRTs and GLAST will be a powerful combination to address these issues. The excellent angular resolution of the NGGRTs will allow detailed mapping of the emission in SNRs. The sensitivity and energy resolution, combined with observations at lower γ-ray and X-ray energies help to elucidate the γ-ray emission mechanism. This may lead to direct the confirmation or elimination of SNRs as the source of cosmic rays.

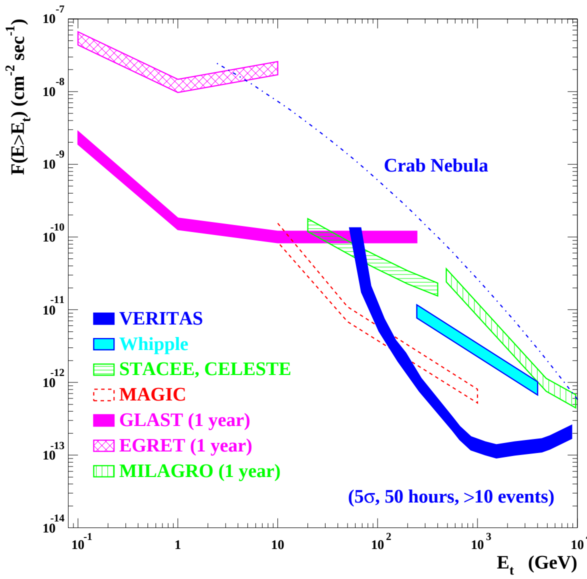

FIG. 10. Comparison of the point source sensitivity of VERITAS to Whipple [56], MAGIC [57], CELESTE/STACEE [59]; [60]; GLAST [62], EGRET [63], and MILAGRO [64].

c. Gamma-ray pulsars The detection of VHE γ-rays would be decisive in favoring the outer gap model over the polar cap model. Six pulsars are detected at EGRET energies and their high energy emission is already seriously constrained by the VHE upper limits. The detection of a pulsed γ-ray signal above 50 GeV would be a major breakthrough.

d. Unidentified galactic EGRET sources The legacy of EGRET may be more than 70 unidentified sources, many of which are in the Galactic plane. The positional uncertainty of these sources make identifications with sources at longer wavelengths unlikely. In the galactic plane, probable sources are SNRs and pulsars, particularly in regions of high IR density (e.g., OB associations), but some may be new types of objects. The NGGRT should have the sensitivity and low energy threshold necessary to detect many of these objects. Detailed studies of these objects with the excellent source location capability of the NGGRTs could lead to many identifications with objects at longer wavelengths. Variability in these objects would be easily identified and measured with the NGGRT.

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