

# High Energy Gamma-Ray Astronomy

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The physics results of high energy  $\gamma$ -ray astronomy are reported, emphasizing recent achievements with ground-based detectors. This includes some of the instrumental developments and latest projects. The fundamental contribution of the field to the question of Cosmic Ray origin is highlighted.

## 1. PHYSICS GOALS

High energy  $\gamma$ -ray astronomy is connected with three important areas of basic science:

- High Energy Astrophysics
- Observational Cosmology
- Astroparticle Physics

Overall and in somewhat simplified terms, **High Energy Astrophysics** concerns itself with the most energetic and violent processes in the Universe. High energy  $\gamma$ -ray astronomy can specifically study the *nonthermal* processes and in a global sense its field is the *Nonthermal Universe*. Having said this, the most interesting objects are those which produce the nonthermal particle populations. I will mention here *Pulsars* and *Supernovae*, and possibly *new types of sources*. The long list of other Galactic topics of interest contains accreting X-ray binaries ( $\mu$ -Quasars), the diffuse Galactic emission, molecular clouds, etc. For a recent review see [1]. The main extragalactic  $\gamma$ -ray detections [2] are for supermassive Black Holes as active galactic nuclei (AGNs) in the centers of galaxies. They have different forms of appearance, from giant *Radio Galaxies* and *Blazars* to *BL Lac objects* with their relativistic jets pointing directly towards us. Possibly a nearby *Starburst Galaxy* has been detected in very high energy  $\gamma$ -rays [3]. I shall leave aside here Gamma Ray Bursts, luminous Quasars or the Extragalactic  $\gamma$ -ray Background and rather come back to them in the last section.

The role of  $\gamma$ -ray astronomy in **Observational Cosmology** concerns cosmic structure formation in terms of stars, galaxies and clusters of galaxies. One topic is the diffuse extragalactic radiation field (CIB) from these objects in the optical/infrared wavelength range. It is not easily measured directly due to dominant foregrounds, from Zodiacal Light to Galactic Cirrus. Pair production of high energy  $\gamma$ -rays on the CIB photons however leads to characteristic absorption features in the  $\gamma$ -ray spectrum of distant sources like AGNs. For given distance and  $\gamma$ -ray source spectrum this determines the CIB spectrum. Including the intergalactic magnetic field, the CIB absorption/CMB Inverse Compton cascade leads to Giant Pair Halos around sources with sufficiently energetic primary  $\gamma$ -ray photon emission  $\gg 10$  TeV [4], whose angular structure and spectrum in principle allow the derivation of CIB spectrum - locally in redshift - as well as absolute distance. This is the  $\gamma$ -ray analog to the Sunyaev-Zel'dovich effect [5] on the CMB in clusters of galaxies and shows the richness of high-energy photon astronomy. A topic for the near future concerns the study of formation and internal evolution of galaxy clusters from their characteristic  $\gamma$ -ray spectrum and morphology (e.g. [6–8]).

In **Astroparticle Physics**  $\geq 30$  TeV  $\gamma$ -ray observations permit an indirect Dark Matter search through the possible detection of generic SUSY WIMP annihilation features in Dark Matter Halos like the one expected in the center of our Galaxy [9]. It is not clear whether this will

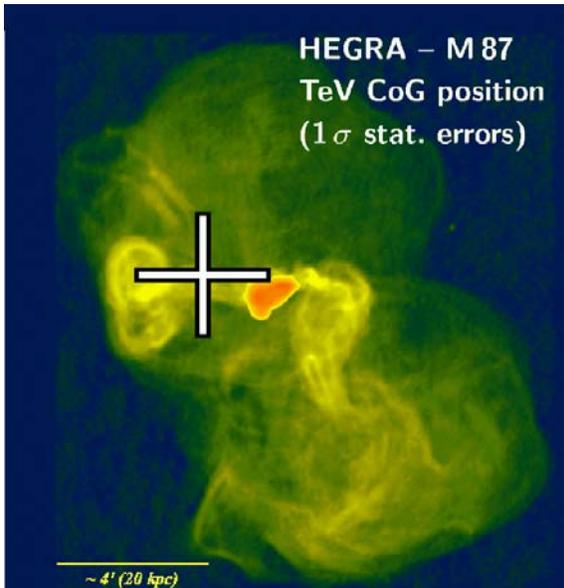


Figure 1. Radio image of M87 and its jet in the Virgo cluster at 90 cm. The cross (statistical  $1\sigma$  errors) marks the position of the TeV  $\gamma$ -ray excess detected by HEGRA [18].

be possible in practice because of a number of astronomical backgrounds, even if such annihilation occurs. However the result would be complementary to a detection of supersymmetric particles in accelerators like the LHC and would go a long way towards the identification of the nonbaryonic Dark Matter constituent(s) in the Universe.  $\gamma$ -ray observations of the Galactic Center are therefore high on the list of all  $\gamma$ -ray instruments that can reach this point in the sky.

### 1.1. Introduction

In many respects high energy  $\gamma$ -ray astronomy is a young field. Major results have been obtained since little more than a decade, and a new generation of mature instruments is only now starting operations. After a short description of the instruments I will mainly discuss results obtained with ground-based detectors. This emphasis justifies itself simply by the more recent develop-

ments in that area. The satellite-based instruments and their achievements have already been reviewed extensively in the past (e.g. [10]).

The talk will be concerned with some of the nonthermal sources mentioned above. Of the diffuse nonthermal particle populations I will discuss the question of Cosmic Ray origin. The dynamically dominant part of this population extends to the "knee" region at a few  $\times 10^{15}$  eV and contains essentially all the energy density in Cosmic Rays. I will indicate that  $\gamma$ -ray astronomy in conjunction with X-ray astronomy and theory is closing in on a physics solution in terms of supernova explosions and their remnants (SNRs). I think that the remaining uncertainties are primarily due to poor  $\gamma$ -ray detection statistics rather than incomplete theoretical understanding.

Beyond the present instruments fascinating developments suggest themselves. I will summarize some of them in the last section.

## 2. GAMMA-RAY INSTRUMENTS

In the past the field was dominated by the suite of *satellite-based* spark chamber detectors with charged particle anticoincidence shields SAS II (1972)  $\Rightarrow$  COS B (1975)  $\Rightarrow$  EGRET (1991), sensitive in the range  $30 \text{ MeV} < E_\gamma < \text{few tens of GeV}$ . Despite their large FoV of several steradian, life time of several years, and reasonable energy resolution  $\Delta E/E \sim 20 \%$ , the low angular resolution  $\geq 1^\circ$  has largely prevented the identification of compact sources. The EGRET instrument found about 300 sources [11], many of them AGNs, but the nature of the majority is still unknown. The logical consequence was the GLAST project, to be launched in late 2006, and its smaller Italian brother AGILE (2004), based on solid state converter/tracker technology and an angular resolution of  $\sim 1/10$  of a degree. GLAST, with an effective detector area  $\sim 1 \text{ m}^2$ , can detect  $\gamma$ -rays up to hundreds of GeV. In practice, statistics will limit the energy range to a few tens of GeV.

The detection area, which is intrinsically small for space detectors, reaches very large values  $\geq 10^4 \text{ m}^2$  for *ground-based detectors* in the form of imaging atmospheric Cherenkov telescopes



Figure 2. The 4-telescope array CANGAROO-III (top). The 4 H.E.S.S. I telescopes (middle). MAGIC telescope (bottom left). VERITAS prototype (bottom right).

(IACTs). Their energy thresholds are about 100 GeV, with  $\Delta E/E \leq 20\%$  and an angular resolution of  $10^{-1}$  degree. Disadvantages are the low observation efficiency  $\leq 10\%$  and the intrinsically small FoV  $\sim 10^{-4}$  sr. About a dozen sources have been found until summer 2003, comparatively well-studied, one of them unidentified.

Astronomical results are mainly from the first generation (Whipple, 10 m) and second generation (CANGAROO-I, 3.8 m; HEGRA,  $5 \times 3.3$  m; CAT  $\sim 5$  m) telescopes. But a third generation of major experiments with 10-fold sensitivity at 1 TeV and energy threshold of 100 GeV or below is beginning to take data at various

stages of completion. They are CANGAROO-III (2001,  $4 \times 10$  m) in Australia, H.E.S.S. I (2002;  $4 \times 12$  m) in Namibia, MAGIC (2003, 17 m) on La Palma, and VERITAS (2003;  $4 - 7 \times 12$  m) on Kitt Peak, Arizona. HEGRA pioneered a stereoscopic array of 5 telescopes operating in coincidence. CANGAROO-III, H.E.S.S. and VERITAS took over this technique, and MAGIC also plans to build a 2nd and possibly a 3rd identical telescope.

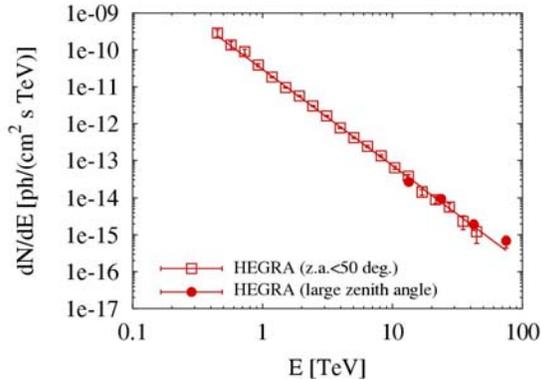


Figure 3. HEGRA differential photon spectrum of the Crab Nebula in the TeV range [12].

### 3. PHYSICS RESULTS

As mentioned before, I will only discuss the most recent results, from 2002 onwards. For general overviews, see [1,2].

The **Crab Nebula** is the strongest steady source in the Northern Sky and has assumed the role of a standard candle. Its emission is dominantly nonthermal, presumably from particles accelerated in the termination shock of a pair plasma wind with a bulk Lorentz factor of about  $10^7$  that carries away the rotational energy loss of the neutron star. Despite its very large magnetic field of  $300 \mu\text{G}$  the emission is dominated by synchrotron radiation. High energy  $\gamma$ -rays had been assumed to be the result of inverse Compton (IC) emission by the synchrotron electrons. Yet their energy spectrum has been recently shown to extend up to at least 70 TeV, unexpected from IC modeling because of the Klein-Nishina effect [12]. An interesting question, also relevant to the acceleration process as such, is whether these very high energy photons come from a hadronic component in the wind with a hard spectrum.

With the HEGRA stereoscopic array it was possible to make a short-exposure scan of the Galactic Plane [13] in search for new Galactic sources. Only upper limits were found. However, by source stacking a combined upper limit

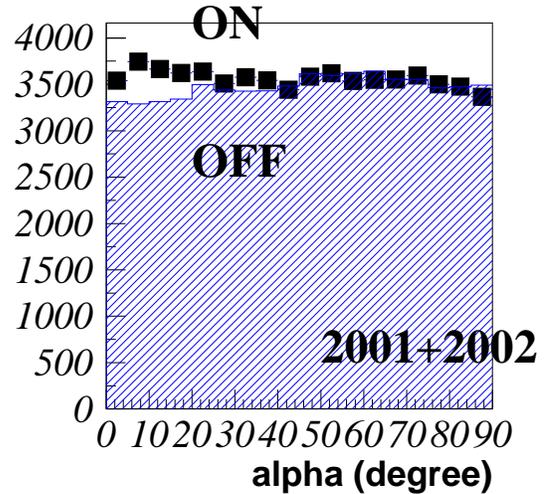


Figure 4. CANGAROO directional (“alpha”) ON-source (*squares*) and OFF-source (*hatched*) distributions for the Galactic Center [14].

at twice the theoretically predicted total  $\pi^0$ -decay flux could be set for the 19 known shell-type SNR candidate sources from the **Galactic SNR population** in the search field. This is still consistent with expectations and indicates a dominant hadronic emission. I will discuss individual SNRs in the last section. The single CANGAROO-II telescope in Australia (a precursor to CANGAROO-III) has found a signal from the **Galactic Center** at 400 GeV [14], thereby confirming the EGRET detection in the GeV range. The combined significance from observations in the two years 2001 and 2002 is approaching  $10 \sigma$  (Fig. 4). The detection has raised high expectations for the results with the full CANGAROO-III and H.E.S.S. I arrays in the Southern Hemisphere that will start operations in 2004. What is needed is a TeV-spectrum and morphological information.

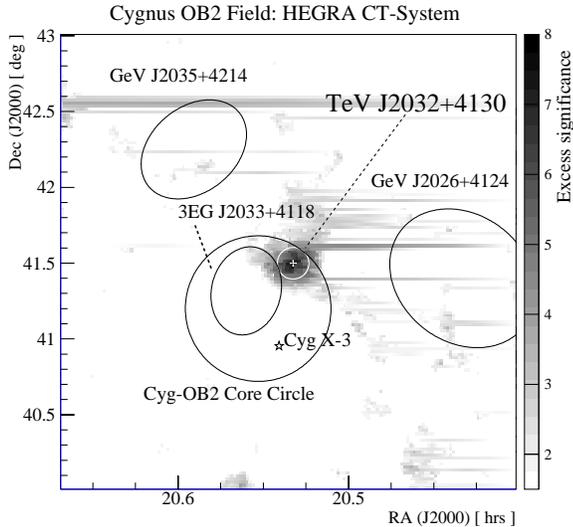


Figure 5. TeV significance map of the Cygnus OB2 field, including GeV error ellipses and positions of known sources [15].

In a serendipitous discovery, the HEGRA array has found an **Unidentified TeV source** at a level of  $7\sigma$  in the Cygnus region of the Galactic disk, just  $0.5^\circ$  north of Cygnus X-3 [15]. The source has no counterpart in any other wavelength range and is marginally extended. The photon spectrum exhibits a hard power law ( $dN/dE \propto E^{-1.9}$ ). From all this evidence, or lack of, the source should be in fact hadronic. Previously it was thought that sources in the TeV region would be associated with astronomical objects of such brightness that they would be well visible at lower energies. However this seems not to be the case. The source is located in the Cygnus OB2 association, one of the most active regions of the Galaxy, with many massive stars. Interactions of their rarefied fast winds might be able to produce such a unique signal [16].

**Active Galactic Nuclei (AGNs)** in the form of BL Lac objects have their relativistic jets pointing towards the observer. The Doppler boosting makes these jets obvious candidates for  $\gamma$ -ray emission. BL Lacs, and more generally

Blazars, are also known to exhibit strong time variations down to fractions of an hour, which may give important clues for the nature of the jet and are detected with TeV instruments but not with the GeV detectors in space. On the other hand very luminous Quasars have not been seen above the GeV range, probably due to internal high energy  $\gamma$ -ray absorption. Thus, for the family of AGNs at large, the GeV-range and the TeV range are complementary. The cosmological aspect of the TeV sources is their absorption on the CIB. The best example found until is the Blazar H1426+428 at redshift  $z \approx 0.13$ . Fig. 6 applies the absorption features from three models of the CIB to the data that show a generic hardening above 1 TeV. The de-absorbed source spectra [17] are only physically "reasonable" for the case a). One task for the new instruments is to find sources at higher  $z$  in order to further strengthen these results.

**Radio Galaxies** show jets at oblique angles. Therefore little Doppler favoritism is expected. It was therefore rather unexpected when HEGRA indeed detected a weak signal from M87 (Fig. 1) in the center of the Virgo cluster at a distance  $\leq 20$  Mpc [18]. The obvious question is whether this shows a new class of extragalactic sources from the AGN family, or whether we have here a first cluster source coming about through the expected confinement of energetic particles in rich clusters over periods that exceed a Hubble time [19]. The question remains undecided at this point, even though it shows the potential of  $\gamma$ -ray astronomy of clusters. This is true for both GLAST and ground-based detectors.

**Starburst Galaxies** presumably harbor many young nonthermal particle sources collectively seen from a distance. And despite the high star formation activity the physics should be similar to that in the Milky Way producing the Cosmic Rays and a large halo. From such a point of view it would be important to detect nearby objects of this kind in high energy  $\gamma$ -rays, such as M82 (at  $\sim 3.2$  Mpc) in the Northern, or NGC253 (at  $\sim 2.5$  Mpc) in the Southern Hemisphere [6]. Past attempts have met mixed success. Despite a long duration observation of about 40 hours, HEGRA was unable to detect M82. Recently

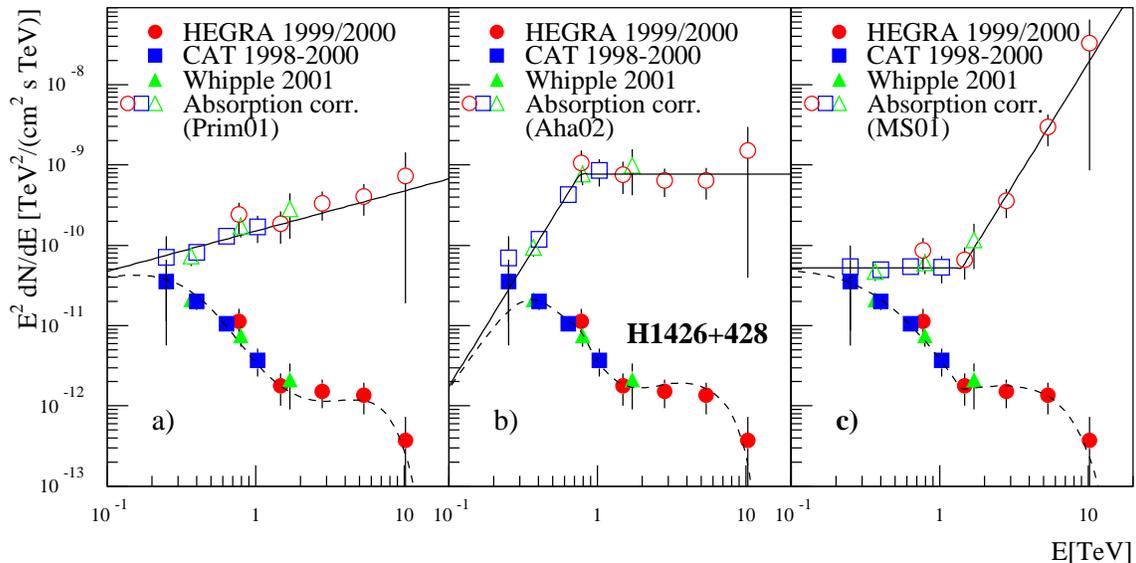


Figure 6. Differential TeV energy spectrum of H1426+428, combining CAT, Whipple and HEGRA data, and de-absorbed for three different CIB models. Absorbed broken power law fits (*solid lines*) are given by the *dashed curves* [17].

however, CANGAROO-II has announced a detection of NGC253 at the  $11\sigma$  level [3]. In contrast to the strictly nuclear starburst of M82, NGC253 should be extended ( $\sim 0.5^\circ$  even in  $\gamma$ -rays), and the full H.E.S.S. I and CANGAROO-III arrays will attempt to study this object in detail.

The serendipitous discovery of the source TeV J2032+4130 in Cygnus has provoked the obvious question as to how many such objects are still hidden in the archives of the past generation of ground-based detectors – EGRET had essentially performed such a sky survey from the very beginning. For a stereoscopic system, where the direction of the primary  $\gamma$ -ray is determined on an event by event basis, such a systematic search has been recently carried out [20]. Excluding previously detected sources, the significance distribution per search bin at  $E_\gamma > 500$  GeV is essentially Gaussian. A number of weak candidate sources exists which turn out to be lined up in the Galactic Plane. These are obvious candidates for future observation with the H.E.S.S. array notwithstanding the conclusion that nothing significant

in **HEGRA's**  $\gamma$ -ray sky has been overlooked. On the other hand, only 3.5% of the total sky had been covered, leaving lots of room for surprises.

#### 4. COSMIC RAY ORIGIN

The question has been one of the prime motivations for  $\gamma$ -ray astronomy to begin with. This concerns the population up to a few PeV and, possibly, to the "ankle" beyond which an extragalactic or even a top down decay origin seems most likely (an area strictly reserved for air shower physics, see [21]). Energetically the Galactic population of SNRs appears as the default solution and this has developed into a folklore in the wider community. Sociologically it is understandable to circumvent one of the long standing physics problems of the last century in this form, scientifically it is not.

Only most recently a combination of SNR observations in hard (synchrotron) X-rays and TeV  $\gamma$ -rays on the one hand, and theory of diffusive shock acceleration on the other, has brought the

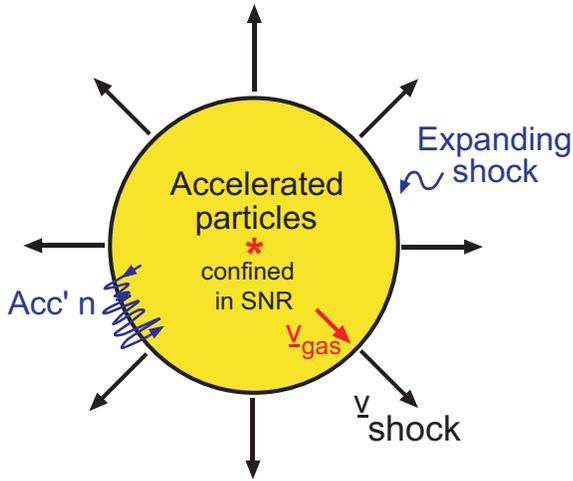


Figure 7. Schematic of diffusive shock acceleration at a Supernova Remnant.

Cosmic Ray origin question close to a physics solution. This development has been summarized in [22]. From the theory side this involves the solution of Fokker-Planck-type kinetic transport equations for nuclei and electrons, nonlinearly coupled to the hydrodynamics of the thermal gas via the pressure gradient of the nonthermal component [23,24]. Nuclei are only *injected* at the quasiparallel parts of the shock surface, leading also to a dipolar morphology for a uniform external field, and requiring a renormalization of the spherically symmetric solution [25]. At least for young SNRs particle scattering occurs at the Bohm limit in an amplified effective field  $B_{eff}$  [26,23], whereas for older remnants it has been argued that high energy particles might escape rather effectively [27] which would make TeV observations difficult. Since  $B_{eff}$  and the injection rate are only calculable within factors of order unity, one can empirically derive their values from the nonlinear character of the observed electron synchrotron spectrum. As a result the well-known SNR SN 1006, assumed to be a SN type Ia as the result of the thermonuclear explosion of an accreting White Dwarf star, can be consistently interpreted in terms of a domi-

nant nuclear Cosmic Ray component accelerated by this object [23,28].

Applying this theory to a different object, I will discuss the case of Cassiopeia A (Cas A), the youngest known SNR in the Galaxy from around the year 1680 A.D., and one of the three SNRs claimed to be detected in TeV  $\gamma$ -rays [29–31]. Cas A is the brightest radio source in the Galaxy and amongst the best-studied objects in the sky, also in other wavelengths. In clear contrast to SN 1006, Cas A is believed to be the result of gravitational collapse of the core of a very massive progenitor, probably a Wolf-Rayet star with a complex sequence of mass-loss phases Blue Supergiant  $\Rightarrow$  Red Supergiant (RSG)  $\Rightarrow$  Wolf-Rayet star  $\Rightarrow$  SN explosion. The interaction of the fast Wolf-Rayet wind with the massive slow RSG wind has presumably created a dense shell with mean density of about  $10 \text{ cm}^{-3}$  whose shocked configuration is identified with the bright ring in the radio synchrotron image (Fig. 8), whereas the present SNR shock is assumed to be already propagating through the unperturbed RSG wind region [32]. The HEGRA system detected Cas A as a weak source in TeV  $\gamma$ -rays at 3.3 % of the Crab flux [31]. The numerical solution of the dynamic equations for the SNR evolution is consistent with a total mechanical SNR energy  $E_{SN} = 4 \times 10^{50}$  erg as well as an extremely high internal field  $B_{eff} = 200 \mu \text{ G}$  downstream of the shock, and of order 1 mG in the shell [24]. For comparison, an estimate from the X-ray morphology yields about 0.1 mG [33].

The spatially integrated overall momentum spectrum of accelerated protons hardens towards the upper cutoff at a few  $\times 10^{14}$  eV, whereas the electrons are subject to synchrotron cooling with a cutoff at about  $10^{13}$  eV. This is clearly visible in the derived synchrotron emission spectrum [24] whose nonlinear convex shape flattens around  $10^{13}$  Hz and thus stays below the infrared point [34] which should contain a thermal dust emission contribution (Fig. 9). The reasonable fit to the data constitutes at the same time a necessary condition for the consistency of the theoretical description.

The shock propagation in a medium of decreasing density is demonstrated by the secular decline

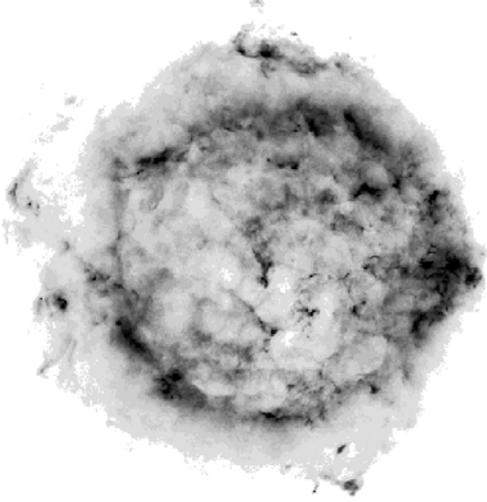


Figure 8. Cas A in 6 cm radio emission, observed with the VLA in 1986 (Courtesy R.J. Tufts).

of the synchrotron flux that is clearly visible in theory and experiment (Fig. 12). In a uniform environment this flux should instead increase monotonically with time.

The high gas density and effective B-field finally lead to a hadronic  $\gamma$ -ray energy flux that exceeds the Bremsstrahlung (NB) and Inverse Compton (IC) fluxes by almost two orders of magnitude at 1 TeV, while remaining clearly below the EGRET upper limit at 100 GeV. This implies a renormalization by a factor 1/6 [25]. The conclusion is that Cas A is a hadronic  $\gamma$ -ray source with a strong dominance of accelerated nuclear Cosmic Rays over the electron component.

Obviously Cas A is a prominent member of the SNR population. At the same time it is clear that an unambiguous model prediction for its  $\gamma$ -ray flux requires a detailed knowledge of the source which can only be obtained by extensive astronomical observations in other wavelength ranges. For these reasons an extrapolation from the two cases of SN 1006 and Cas A to the effect of the Galactic SNR population is not without risk. Fu-

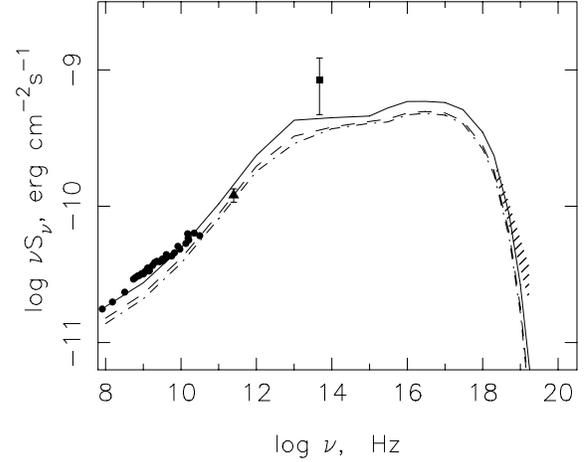


Figure 9. Radio and X-ray emission from Cas A, observed in different years. The model curves correspond to the epochs 1970, 2003 and 2022 [24].

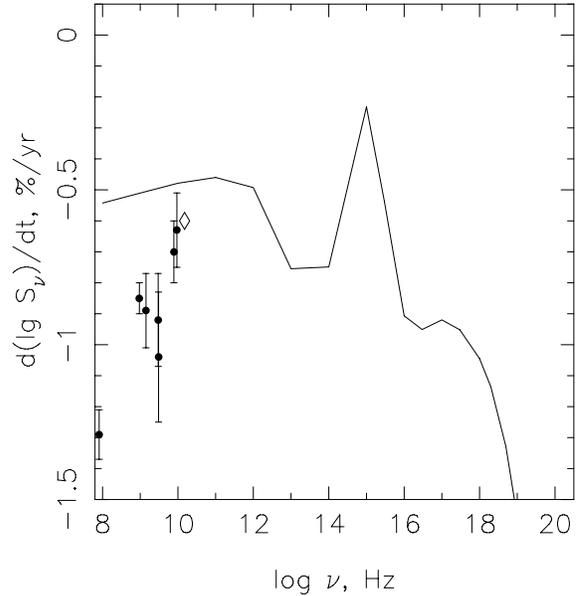


Figure 10. Secular decline of the synchrotron flux from Cas A, in percent per yr [24].

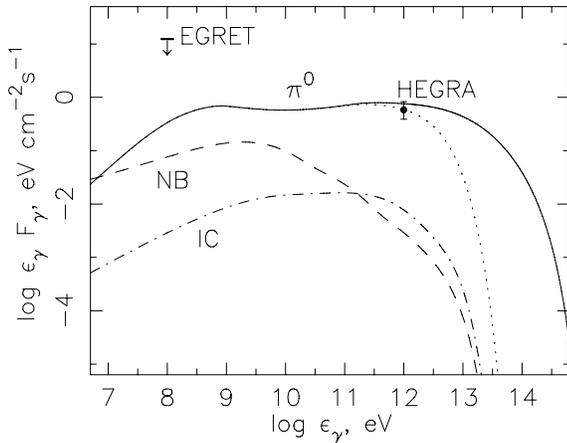


Figure 11. Predicted  $\gamma$ -ray energy flux from Cas A [24].

ture observations in high energy  $\gamma$ -rays and other wavelength ranges, especially of the "diffuse"  $\gamma$ -ray background in the Galactic disk, are desirable to obtain a statistically impeccable solution.

## 5. PERSPECTIVES

In late 2003 the full imaging array H.E.S.S. I, and probably also CANGAROO-III, will go into operations. They will do everything faster and better. But in my view they should not start collecting stamps! We should rather (i) confront theory of Cosmic Ray origin with detailed  $\gamma$ -ray spectra and morphologies and increase the source statistics (ii) attempt to determine the spectrum of the diffuse  $\gamma$ -ray background in the Galactic plane (iii) give Pair Halos a try, not only AGNs, and determine the CIB up to  $z \sim 0.5$ , (iv) detect rich clusters of galaxies (v) start an determined search for Dark Matter in the center of the Galaxy and other nearby Dark Matter Halos, in complementarity to LHC up to about 10 TeV, and alone beyond.

GLAST is scheduled to start operations still in 2006. With its large field of view its sky survey will be unsurpassed in the GeV range. GLAST should be able to identify the majority

of the EGRET sources and to investigate them physically. As regards Cosmic Ray propagation in the Galaxy, passive  $\gamma$ -ray sources will play a large role following the tradition of satellite  $\gamma$ -ray astronomy. Its is not obvious how much will be learned from the expected dramatic increase of the AGN population. But clusters of galaxies may become detectable, and GLAST is expected to study their morphology in an attempt to find recent accretion events. A complementary program with ground-based arrays suggests itself.

The aim of a next generation imaging Cherenkov array must be a threshold of a few GeV, the theoretical limit for this technique. This implies energies in the satellite range with effective detector areas exceeding  $10^4 \text{ m}^2$ . A well-known idea is the Atacama project 5@5 (= 5 GeV threshold energy at 5 km altitude) at the ALMA site in Chile. In a detailed Monte Carlo study [35] for such a stereo system of 5 large ( $600\text{m}^2$ ) imaging Cherenkov telescopes an important signal/noise improvement has been confirmed which is the result of being closer to the shower maximum at this height. The size and complexity of such an array suggest a worldwide collaboration beyond the European institutions involved in the present design studies. Fig. 12 shows a possible configuration. Such an instrument will be complementary to high energy arrays like H.E.S.S. Another idea is ECO (= European Cherenkov Observatory) on La Palma at 2100 m a.s.l., emphasizing even larger mirrors and employing fast optical detectors with improved quantum efficiency that are talked about since many years. Monte Carlo studies are under way [36].

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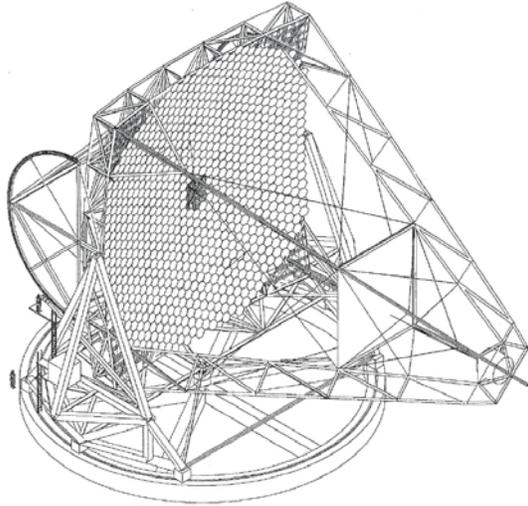


Figure 12. Configuration of a 600m<sup>2</sup> Cherenkov telescope, with steel structure and parabolic mirror support, for a 5 km altitude array. Not yet adapted to high altitude conditions.

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