Invited, Rapporteur, and Highlight papers of ICRC 2001: 3

ICRC 2001

Gamma-ray astronomy of cosmic rays

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Abstract. Many of the basic problems in the astrophysics of charged Cosmic Rays remain on principle unresolved by in situ observations in the Solar System due to the chaotic nature of the propagation of these particles in Interstellar space. This concerns the existence and the nature of localized individual particle sources as well as the transport in the Galaxy and establishes the need for astronomical observations of secondary gamma-rays. The only exception may be the highest energy particles at energies around 10^{20} eV which possibly reach us on straight line orbits from their production sites. Recently such gamma-ray observations, both in space and on the ground, have made great progress even though the instrumental sensitivities are still low. It is argued that two basic questions, regarding first of all the Supernova Remnant source hypothesis and secondly the contributions to the diffuse gamma-ray background, have come close to an empirical resolution. Apart from motivations deriving from extragalactic astronomy this expectation is at the root of the construction of a new generation of high-sensitivity gamma-ray instruments. As a representative example the H.E.S.S. array of atmospheric Cherenkov telescopes is described.

1 Introduction

The International Cosmic Ray Conferences have made it a tradition that a Lecture is given in honor of Victor Franz (Francis) Hess. This gives me the opportunity to recount his discovery in 1912 which initiated the era of Cosmic Ray research and paved the way for the development of particle physics. The realization of the truly historic significance of this discovery appears to be generally growing in the physics community. As part of this awareness it is interesting to note recent efforts at the Universities of Innsbruck and Vienna to emphasize and consolidate the memory of the activities of Hess in Austria[1].

I will then summarize our present knowledge about Galactic Cosmic Rays (CRs) from in situ observations on the ground and in satellite experiments above the atmosphere. In doing so I emphasize the lower energy range, below the so-called "knee" of the energy spectrum near 10^{15} eV, because it contains the overwhelming part of the CR energy density that determines the degree of collective CR interaction with the rest of the Interstellar Medium. The conclusion is, as we know, that the CRs in our local environment constitute a relativistic nonthermal component of Interstellar Matter whose energy density compares to all other relevant energy densities like the turbulent and thermal energy density of the thermal gas and the Interstellar magnetic field energy density. If true elsewhere in the Galaxy and beyond - and there is every reason to assume this - then the CR component is an significant dynamical element in Interstellar as well as in Intergalactic space on sufficiently large spatial scales, and the question of the CR sources becomes a matter of global astronomical importance.

For these reasons we cannot discuss CR transport independently of the dynamics of the interstellar gas and magnetic field. Basically this nonlinear picture goes back to 1966 when Parker (1966) for the first time connected the formation of large scale gas clouds in the Galactic disk with the buoyant rise of the CRs in rarefied magnetized bubbles, proposing that this should lead to their eventual escape to Intergalactic space. Certainly, the process has to compete with diffusive escape in a CR-driven Galactic Wind as emphasized more recently again by Breitschwerdt et al. (1993) and Ptuskin et al. (1997) and it is difficult to estimate quantitatively. But its importance for the development of CR astrophysics is undisputed.

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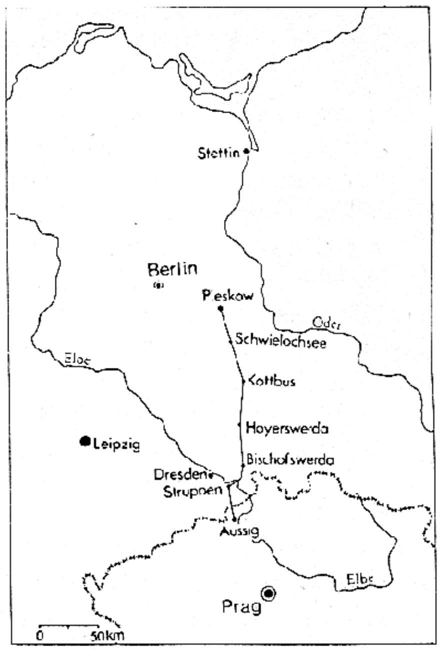
[1]See http://physik.uibk.ac.at/hephy/Hess/homepage/. This Web site also contains an article in "Current Biography Yearbook 1963" which gives an interesting and moving description of his life-story (Moritz, 1963).



Route des Entdeckungsfluges der kosmischen Strahlung.

Fig. 1. The flight on August 7, 1912, started in Aussig in then Bohemia at 06:12 and reached the maximum height of 5350 m at 10:45. The landing took place near Pieskow in Brandenburg at 12:15.

Attempts to verify the validity and the limitations of such a picture require CR observations in the depth of the Cosmos, at least extending across the Galaxy. This type of observations can in a direct form only be done on secondary neutral particles, gamma-rays and neutrinos, whose trajectories point back to their origin, and I shall discuss gamma-ray observations here.

My main topics will be recent gamma-ray investigations of presumed localized CR sources and of CR propagation in the Galaxy. This concerns first of all the Supernova Remnant source hypothesis and the present observational results in comparison with theoretical acceleration models. With regard to CR transport and to the key question how representative the CR properties near the Solar System are for the Galaxy as a whole, I will discuss the unexpectedly hard spectrum of the diffuse gamma-ray flux from the Galactic disk, its implications and possible explanation. The observed very small diffuse, radial gamma-ray gradient in the Galactic disk poses another problem for CR propagation theory. It may again be a nonlinear effect in the sense that an increase of CR production due to a spatial concentration of sources leads to a compensatory local velocity enhancement of the Galactic Wind which prevents the expected increase of the local particle density.

Accompanied and partly driven by theoretical developments gamma-ray observations of Galactic and Extragalactic sources have made significant progress over the last years, despite the rather low detector sensitivities. This has encouraged the construction of a new generation of larger and more sensitive instruments. I will conclude this lecture with a description of a representative experiment, the ground-based stereoscopic H.E.S.S. array of imaging atmospheric Cherenkov telescopes. It is named in honor of Victor Hess and is being built in Namibia.

2 The time of Victor Hess

In his balloon flights, Hess brought sealed ionization chambers into the upper atmosphere to measure the rate of ionization induced as a function of height. From about 1500 m above ground the ionization increased monotonically with height. In his highest flight on August 7, 1912 (Fig. 1,2), at the maximum altitude of 5300 m the ionization rate increased by a factor of two relative to the ground which could not have come from radioactive material on the ground or in the air.

Hess bei Ballonlandung (1912).

Fig. 2. Victor Hess (in the middle) and his crew in the balloon gondola after the landing in Pieskow.

The flight took about 6 hours and after the subsequent checks the balloon crew could return to Vienna by night train. In 1912 the geographical world of experiments was still small!

Fig. 3. The participants of the Symposium on Cosmic Rays, Chicago 1939. A number of individuals are identified by name on the bottom of the figure by the author (archive Max-Planck-Institut für Krenphysik).

The conclusion that Hess (1912) could finally draw was clear and surprising: "The results ... appear most likely explainable by the assumption that a radiation of very high penetration power enters our atmosphere from above[2]". Subsequent balloon measurements at even much greater altitudes, in particular by W. Kohlhörster, confirmed and strengthened the result.

The history of the later, difficult and sometimes controversial investigations into the nature of these very energetic particles is a fairly long one. Eventually, after twenty years of experimentation by many groups and the development of important new techniques, it was found that the Cosmic Rays above the atmosphere are mostly positively charged nuclear particles, in fact mainly protons. These particles became vital tools for the emerging field of particle physics and all of the new particles discovered until the beginnings of the accelerator era in the mid-fifties were found in CR interactions. Fig. 3 is a photograph of the participants in the *Symposium on Cosmic Rays* held 1939 in Chicago, showing Victor Hess in the center together with many other well-known physicists: Werner Heisenberg, Walter Bothe, Arthur Holly Compton, Robert Oppenheimer, Edward Teller, Pierre Auger, Carl Anderson, Hans Bethe, and others. I got this picture originally from Professor Maurice Shapiro who is at the conference here in Hamburg: you can see him in the upper left hand corner as a young graduate student.

[2] In the German original: "Die Ergebnisse ... scheinen am ehesten durch die Annahme erklärt werden zu können, dass eine Strahlung von sehr hoher Durchdringungskraft von oben her in unsere Atmosphäre eindringt."

3 Cosmic Rays near the Solar System

3.1 Primary particle energy spectra, energetics

Direct measurements of CRs are made nowadays with sophisticated detector combinations on satellites, balloons, and (at energies above 10^{15} eV/nucleon) on the ground. The resulting energy spectra are similar for many chemical elements considered to be primary, i.e. directly accelerated with little subsequent nuclear transformations. There is also a primary CR electron component and at GeV energies its flux is two orders of magnitude below that for protons. Most impressively, the all-particle energy spectrum extends over more than 11 orders of magnitude in energy. It is the prototype of a nonthermal spectrum, without a sign for a characteristic energy scale (Fig. 4).

The differential energy spectrum is approximately a power law in energy $E \propto E^{-2.75}$ beyond the range of influence from the Sun, for 10^{10} eV $< E <$ few 10^{15} eV. The spectral features at several 10^{15} eV and 10^{18} eV, respectively, may indicate different particle sources, or alternatively, different energy dependences of the propagation conditions in the separate energy regions. The corresponding estimate of the CR energy density E_{CR} in the neighborhood of the Solar System is of the order of 1 eV/cm^{-3}, about equal to the thermal energy density E_{gas} of the Interstellar gas as well as the typical Interstellar magnetic energy E_{mag}, measured by other means: $E_{CR} \sim E_{gas} \sim E_{mag}$. I have discussed the significance of this equality before.

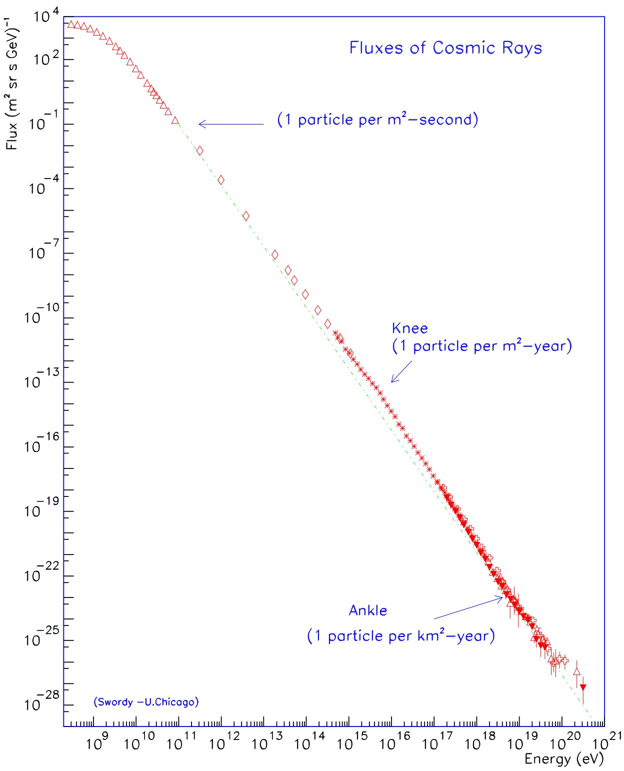


Fig. 4. The all-particle CR energy spectrum. For $E \gtrsim 10$ GeV, the spectrum is a power law, slightly steepening at a few 10^{15} eV, the so-called Knee, and hardening at a few 10^{18} eV, the so-called Ankle. (Adapted from Cronin et al. 1997; courtesy S. Swordy.)

How should we picture the overall energy distribution of the thermal gas plus the CRs as they coexist in a given volume element in space? This question has no unique answer because, even if the gas and the CRs are energized at the same place in a cosmic accelerator like a Solar Flare or a Supernova Remnant, their spatial propagation can be very different. Nevertheless, at such an accelerator, the nonthermal power law distribution of the CRs should grow out of the thermal distribution somewhere above the gas thermal energy. This can be seen in Fig. 5 which shows an analytical calculation of diffusive particle acceleration at a shock wave. The example also indicates the relative energetics: despite the fact that the particle number density of the gas exceeds that of the CRs by three orders of magnitude, the inverse is roughly true for the mean particle energies. Therefore such a process can indeed lead to approximately equal energy densities of the two components.

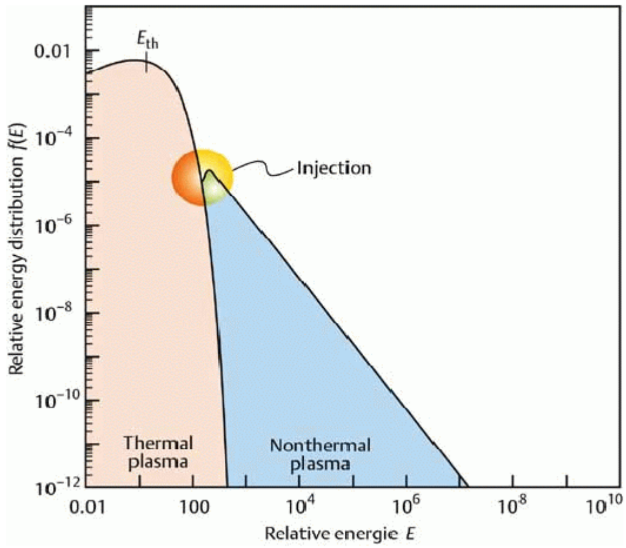


Fig. 5. Totalenergy distribution of thermal plasma (gas) plus nonthermal plasma (CRs) near a diffusively accelerating shock wave: the thermal (Maxwellian) energy distribution joins rather smoothly to the nonthermal power law CR distribution at an "injection" energy that is several times larger than the mean thermal energy E_{th}. Only supra-thermal particles above this injection energy can participate in the collective acceleration process (adapted from Malkov and Völk, 1998; courtesy "Sterne und Weltraum").

3.2 Cosmic Ray source spectra, composition

The observed CR energy spectra are not necessarily identical with the spectra of the particles as they are emitted from their sources. The connection between the two is rather given by the particle propagation properties. Observations show that the ratio between the energy spectra of CR spallation products and their primary particles decreases with energy (Fig. 6). For energies above 10 GeV/nucleon this translates directly into a corresponding energy dependence of the average amount of Interstellar matter "seen" by CR particles. If we assume the particles to be produced deeply inside the dense Galactic gas disk then this implies a shorter residence time there for higher energy particles than for those of lower energy before they eventually escape to Intergalactic Space.

Let us now in addition take the particle sources as well as the particles released from them to be uniformly distributed across the Galactic disk that includes also the Solar System

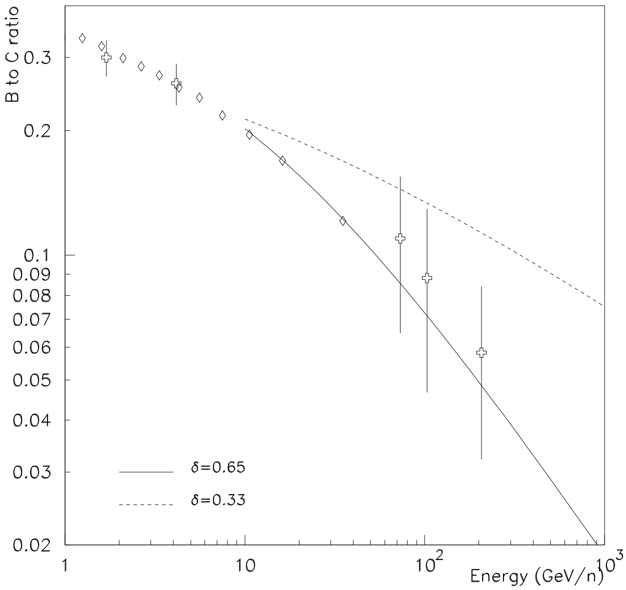


Fig. 6. The measured ratio of (secondary) Boron to (primary) Carbon nuclei as a function of energy/nucleon up to 200 GeV/nucleon: diamond-shaped points from Engelmann et al. (1990), crosses from Swordy et al. (1990). Two different power law dependences $\propto (E/\mathrm{nucleon})^{-\delta}$ are indicated for comparison. (Courtesy S. Swordy.)

where we measure. Then one can infer from such local measurements that the source spectra for various different elements are very hard: $dN/dE \propto (E/\mathrm{nucleon})^{-2.1}$ at least up to $E/\mathrm{nucleon} \sim 10^3$ GeV/nucleon, i.e. up to the TeV region ($10^3\ \mathrm{GeV} = 1\,\mathrm{TeV}$).

The chemical composition at the sources is much less known than the energy spectra. However, up to an energy of 100 GeV/nucleon the source material corresponds to rather normal Interstellar Medium material (gas and dust), with a number of characteristic deviations (see below). At higher energies, no determination of source spectra has been possible until now. From all we know, in the arriving CRs heavier nuclei appear to become more abundant with increasing energy, also beyond the knee. Above the ankle virtually nothing is known about the composition; the arriving particles could even be gamma-rays. It is clear that this is a wide open field and several new experiments with sophisticated instrumentation are operating or are being built at present. They will be among the main topics at this conference.

4 The need for gamma-ray observations

The most fundamental questions in CR astrophysics concern the individual sources - if such localized accelerators exist in the first place - and the transport of these ultrarelativistic particles in the Galaxy. Due to the deviation of charged particle orbits from a linear path in the chaotic interstellar magnetic fields, localized accelerators cannot be identified by observation of such particles near the Earth, as indicated in the cartoon Fig. 7. In the same sense also the propagation in the Galaxy remains unknown, apart from the energy dependence of the average matter density which the CRs have seen. Therefore there is a need for astronomical observations that give directional and, with the aid of multi-wavelength observations, also distance information.

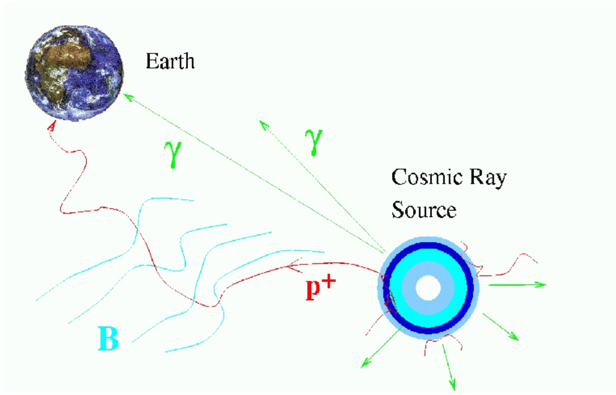


Fig. 7. Charged particles p^+ emitted from a localized Cosmic Ray source have followed chaotic orbits in the interstellar magnetic field B when they reach the Earth. Therefore their arrival direction does not point back to the source as do γ-rays. (Courtesy G. Pühlhofer.)

In a direct form this can be done with high energy ($\gtrsim 0.1$ GeV) γ-rays or with neutrinos as neutral interaction products from CR collisions with thermal gas atoms (pion-decay, electron Bremsstrahlung), or Inverse Compton effect on photon fields, mainly the microwave background radiation. Integrated along the line of sight, the Inverse Compton γ-ray emission from CR electrons turns out to be comparable in magnitude with that from nucleon-induced pion decay, given typical interstellar gas densities. Since such secondary γ-rays and neutrinos already have energies in the range of interest for the sources of the charged CRs, they portray the high energy CRs at first hand. Obviously the program is then the following: with the aid of γ-ray or neutrino observations individual CR sources may be found from amongst the regions of localized emission. Under this assumption of source localization the spatial and spectral dependence of the diffuse γ-ray and neutrino emission is then determined by the transport properties of the CRs outside the sources.

Apart from these direct astronomical signals there is a further indicator of growing importance. This is high frequency synchrotron emission, sometimes reaching hard X-ray energies. But the inference on the radiating energetic electrons is less direct; secondary information like polarization or a clearly nonthermal frequency spectrum must be available to distinguish this signal from Bremsstrahlung emission by electrons of comparable energy. In fact, most energetic objects like Pulsars, Supernova Remnants, or entire galaxies, emit radio synchrotron radiation which is of great value to ascertain the spatial extent of the CR distribution and of the magnetic field, as well as their equipartition strengths. Beyond that, the synchrotron interpretation of seemingly nonthermal hard X-ray emission from several Pulsars and Supernova Remnants has been taken as an indication that electrons

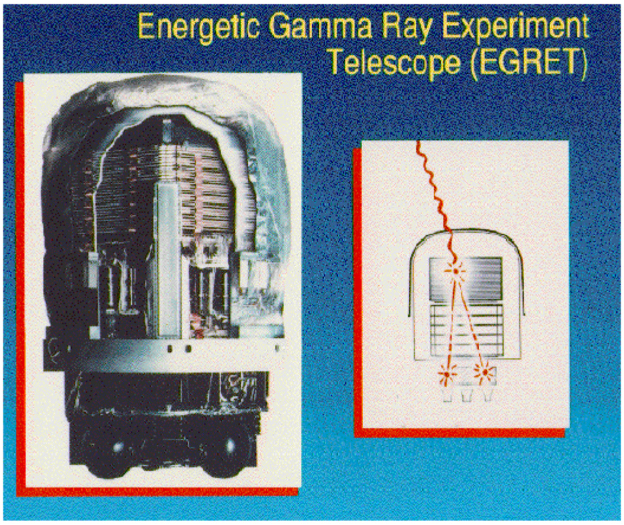


Fig. 8. Cut-away of the Energetic Gamma Ray Experiment Telescope (EGRET) on the Compton Gamma Ray Observatory. The track of the pair produced by the interaction of the primary γ-ray in the upper part of the detector is made visible in an adjacent spark chamber (right panel). The detector is surrounded by an anti-coincidence hood where, in contrast to γ-rays, charged CRs produce a scintillator signal (left panel).

in the tens of TeV energy range are present in these objects. To the extent that this is the case, there is little doubt that also CR nucleons should have been accelerated.

The field of radio or X-ray observations is not my topic here. But I shall make use of their results in discussing the search for the CR sources. Neutrino astronomy at high energies $\gtrsim 1\,\mathrm{GeV}$ is still in the R & D phase. Therefore I will concentrate here on γ-ray astronomy. Above $0.1\,\mathrm{GeV}$ the dominant instruments are directionally sensitive γ-ray detectors on satellites above the atmosphere and, for energies $\gtrsim 10\,\mathrm{GeV}$, ground-based imaging atmospheric Cherenkov telescopes. There exist also interesting non-imaging γ-ray detectors using Solar power plants. They will presumably enhance the ground based capabilities in the future.

5 Gamma-ray instruments

At the energies concerned, pair production is the dominant process for γ-ray absorption in matter. In satellite instruments the pair is directly observed (Fig. 8).

In addition, a satellite detector can be furnished with an anti-coincidence shield to effectively discriminate against the dominant background of charged CRs. Previous instruments on the satellites SAS-II, Cos B, and CGRO were characterized by a large field of view $\Delta\Omega$ of order π, and a relatively small effective area below $1\ \mathrm{m}^2$ for γ-ray energies between $30\ \mathrm{MeV}$ and a few GeV.

Ground-based imaging atmospheric Cherenkov telescopes on the other hand (Fig. 9) detect the Cherenkov light from the secondary electrons and positrons of the electromagnetic shower in the atmosphere that is produced by the primary cosmic γ-ray, with a maximum particle density at a height of about 10 km. The most important instruments are the Whipple, CANGAROO (Collaboration of Australia and Nippon for a GAmma Ray Observatory in the Outback), CAT (Cherenkov Array at Themis), and HEGRA (High Energy Gamma Ray Astronomy) telescopes. The strong background due to the Cherenkov emission from hadronic showers caused by charged CR nuclei is largely removed by analysis of the image in the telescope's focal plane detector. This is possible because hadronic showers are typically much broader than electromagnetic showers, and not even approximately rotationally symmetric around the shower axis. For the background reduction it is therefore extremely valuable to use a stereoscopic method in which several telescopes are viewing the same shower in coincidence from different directions within the ~ 1 degree Cherenkov light cone (Fig. 10). Such a land surveyor's technique also allows the determination of the arrival direction and of the γ-ray energy on an event by event basis. The instruments are generally characterized by a small field of view of a few degrees, and a very large effective area of the order of $10^5\ \mathrm{m}^2$, with threshold energies of a few 100 GeV up to TeV energies at present.

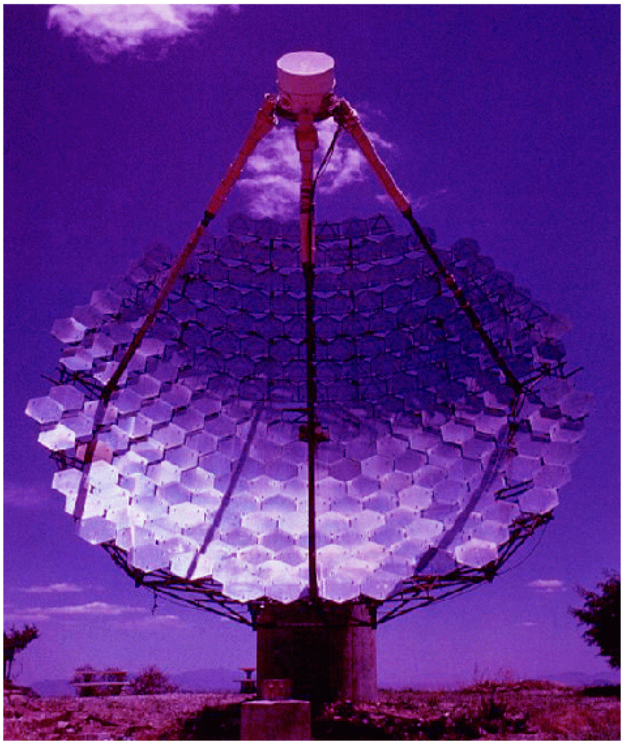


Fig. 9. Photograph of the pioneering Whipple imaging atmospheric Cherenkov telescope in Arizona, USA. With a diameter of $10\,\mathrm{m}$ it has been until recently the largest operating imaging telescope. The tessellated mirror consists of 248 spherically shaped hexagonally cut mirrors, each $61\,\mathrm{cm}$ across. In the focus a fast camera whose pixels are photomultipliers records the shower image against the night sky background (Cawley et al. 1990).

A well-known example of an almost entirely nonthermal source is the Crab Nebula, powered by the relativistic wind

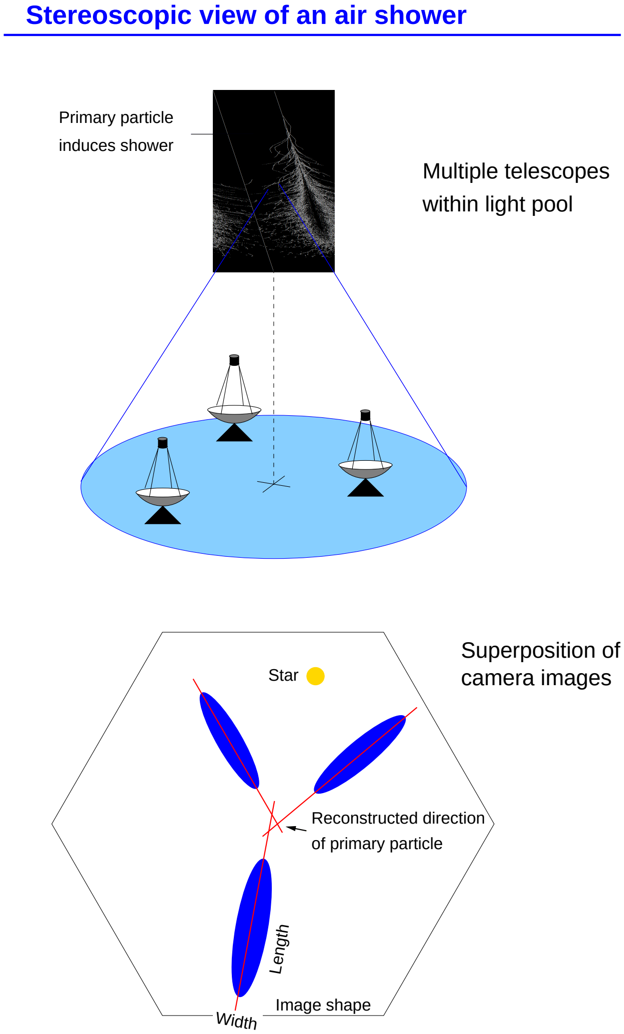


Fig. 10. Stereoscopic γ-ray observation by several telescopes positioned in the Cherenkov cone of an atmospheric shower. The generally elliptical images, superposed into one of the focal plane cameras, determine the arrival direction through the intersection point of their extrapolated major axes. In analogous fashion also the impact point of the shower axis on the ground is determined. This method was first introduced in the HEGRA stereoscopic system.

of electron-positron pairs from the Crab Pulsar (Fig. 11). In the γ-ray regime the satellite instruments are assumed to document the transition from the synchrotron radiation at lower energies to the Inverse Compton emission that dominates for E_γ above 1 GeV and is eventually detected by the Cherenkov detectors.

6 The Supernova Remnant (SNR) source hypothesis

Since the proposal by Baade and Zwicky (1934) Supernova explosions are the primarily considered candidates for the CR sources up to the knee of the spectrum[3]. The argument from today's point of view concerns diffuse Supernova Remnants, not Pulsars nor Black Holes, and consists of three elements:

1. As an ensemble, Supernova Remnants imply the largest mechanical energy release $(dE/dt)_{SN}$ into the Interstellar Medium which is available as free energy for particle acceleration and heating of the thermal gas:

$$\begin{aligned}(dE/dt)_{SN} &= \nu_{SN} \times E_{SN,mech} \sim 10^{42}\mathrm{erg/s} \\ &\quad \times \nu_{SN}/(1/30yr) \times E_{SN,mech}/(10^{51}\mathrm{erg}) \\ &\quad \sim 10 \times (dE/dt)_{CR},\end{aligned}$$

in the Galaxy, where ν_{SN} and E_{SN} denote the Galactic Supernova rate and the mechanical energy output per SN, respectively, and $(dE/dt)_{CR}$ is the total amount of energy leaving the Galaxy in the form of CRs. Thus SNRs can indeed supply the very large amount of energy required even though not by a large margin.

2. Diffusive shock acceleration at the leading outer SNR shock leads to a hard momentum spectrum, approximately $\propto p^{-2}$. Given the above requirement of high efficiency, acceleration must be a nonlinear dynamic process which indeed it is.

3. The expected elemental composition of the accelerated component is basically given by that of average interstellar matter - somewhat enriched by progenitor wind material - swept up by the Supernova blast wave. A smaller contribution is expected from ejected material of the progenitor stars if it is either accelerated directly by secondary processes or has modified the circumstellar gas of neighboring stars, exploding subsequently. This is essentially what the measurements require.

There may be a theoretical problem with the SNR origin hypothesis, since the cutoff energy predicted by quasilinear acceleration models lies typically an order of magnitude below the "knee". However, I do not think that this is an unsurmountable obstacle. The theory is still incomplete, despite the sophistication it has reached in the last years. And there are reasons to believe that a full consideration of the strongly nonlinear plasma physics of the acceleration process will remove the deficiency.

All in all the arguments are quite persuasive. Yet this is still only theory and we better turn to observations. They present a complex picture.

6.1 Detected SNRs

The EGRET experiment on the Compton Gamma Ray Observatory has detected many Galactic γ-ray sources. Up to now the majority is still not identified with known astronomical objects.

Also several SNRs with typical diameters smaller than a 1° have been detected, but the γ-rays are not firmly due to

[3] In their seminal paper Baade and Zwicky also assumed for Supernova explosions "... that a considerable part of the total radiation E_T is emitted in the form of very hard rays or energetic particles", and advanced the view "... that a super-nova represents the transition of an ordinary star into a *neutron star*, consisting mainly of neutrons.".

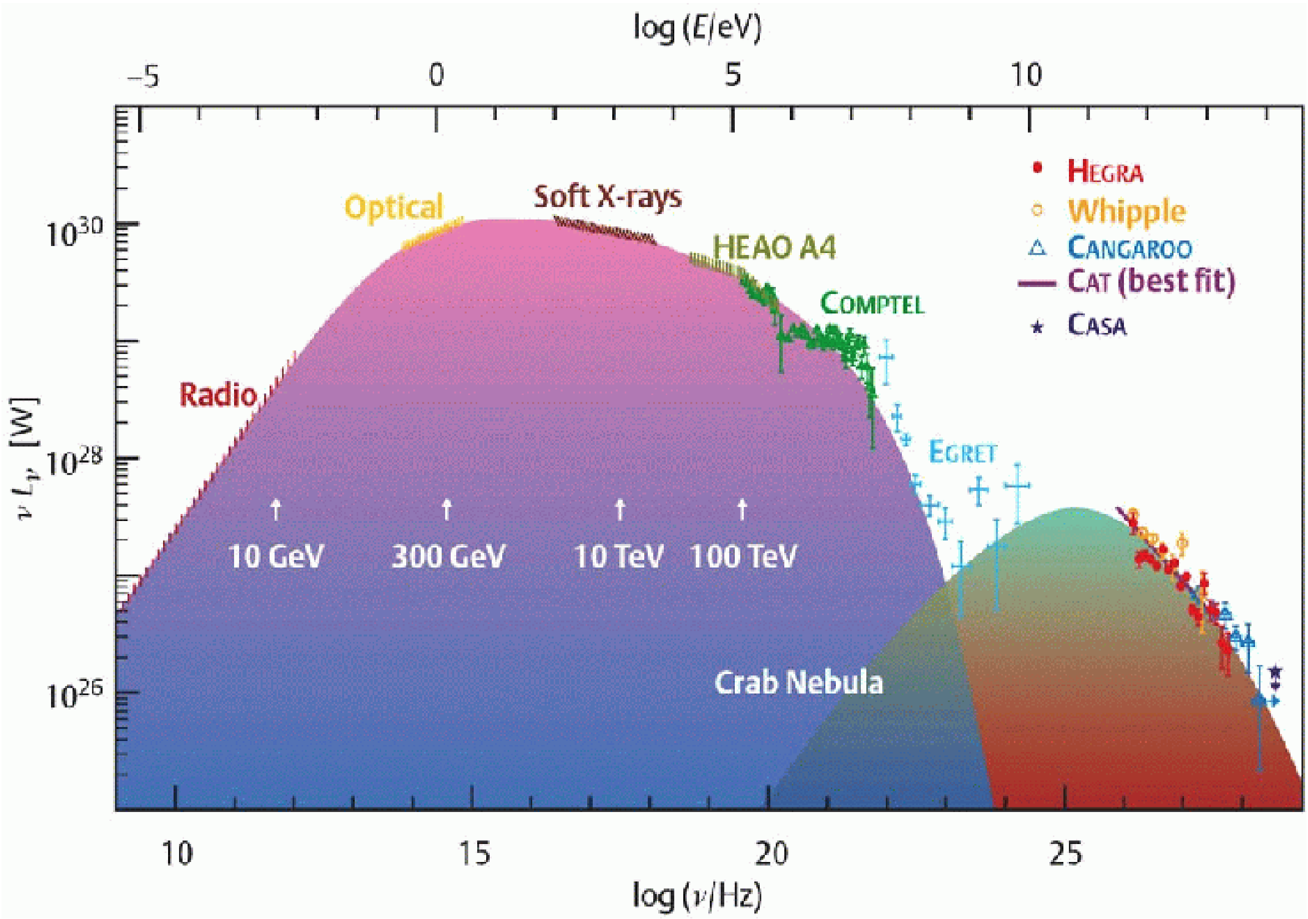


Fig. 11. Spectral energy distribution of the emission from the Crab Nebula. The electron energies producing the dominant synchrotron peak at lower energies are indicated by the arrows. The CGRO γ-telescopes COMPTEL and EGRET determine the synchrotron fall-off and the transition to the Inverse Compton peak expected at some tens of GeV, and indicated by the Cherenkov telescope measurements. (Adapted from Aharonian and Atoyan (1998); Courtesy "Sterne und Weltraum".)

SNR shock acceleration. They might as well be rather due to Pulsars or Pulsar Nebulae. The identification of SNRs in the GeV energy region is in fact very difficult, due to the steep spectrum of the strong diffuse γ-ray background from the CRs in the Interstellar Medium. This steep fall-off of the diffuse background spectrum combined with the assumed hard source spectra suggests significantly better detection capabilities at higher energies, in particular in the TeV range. As a consequence ground based Cherenkov telescopes appear more suitable detectors, although the present generation of instruments is only marginally sensitive for the detection of SNRs. This is even true for luminous, very nearby objects.

Up to now three such TeV-detections have been reported (Fig. 12, 13, 14). They are on the 5σ level and still need confirmation by independent groups:

(a) SN 1006 and SNR RX J1713.7-3946 in the Southern Hemisphere (CANGAROO telescope)

(b) Cassiopeia A in the Northern Sky (HEGRA telescope system).

From published results, there exist basically single flux values around 1 TeV, with minimum information on the spec-

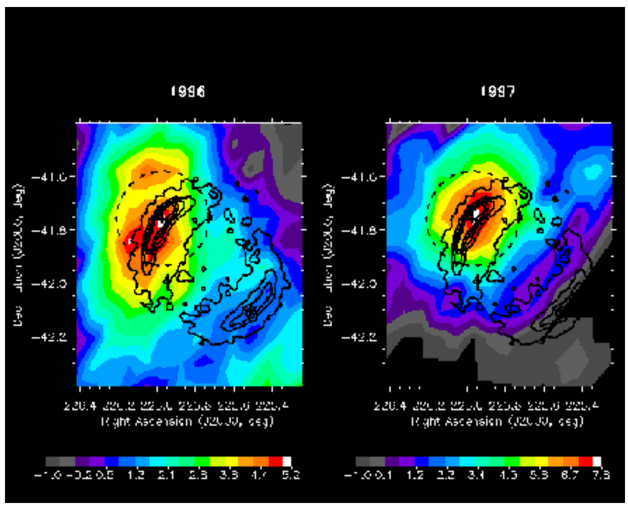


Fig. 12. TeV γ-ray significance map from CANGAROO (Tanimori et al. 1998) for SN 1006, superposed on the nonthermal X-ray intensity contours obtained by Koyama et al. (1995) with the ASCA satellite.

trum. All three sources have also been detected in nonthermal X-rays, supposedly synchrotron radiation from multi-TeV electrons. With simple assumptions the γ-ray flux can be made consistent with Inverse Compton emission of such high energy electrons. This is rather persuasive given the fact that the X-ray emission of both Southern sources is even dominated by the nonthermal emission. In particular for SN 1006, a SN type Ia in a uniform Interstellar Medium, with a possibly low gas density, a low magnetic field strength $B \approx 6\mu$Gauss allows consistency between the X-ray synchrotron emission on the one hand, and Inverse Compton TeV γ-ray radiation on the Cosmic Microwave Background on the other - by the same electrons - consistent with a differential spectral index of -2. A qualitatively similar conclusion has been drawn for the emission from SNR RX J1713.7-3946, and more results are expected at this conference from the new 10 m CANGAROO-II telescope. This does not claim that there are no hadronic γ-rays, but it says that they may simply not be needed to explain the reported γ-ray results.

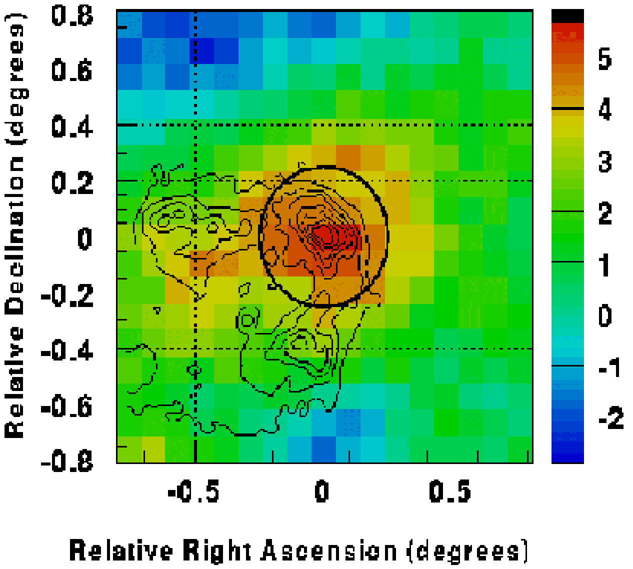


Fig. 13. TeV γ-ray significance maps from CANGAROO (Muraishi et al. 2000), superposed on the nonthermal X-ray intensity contours for SNR RX J1713.7-3946 from ASCA observations by Koyama et al. (1997).

This has led some researchers to a far reaching and pessimistic conclusion. It says that the TeV γ-rays from such individual objects are probably due to Inverse Compton collisions of CR electrons with background photons alone and, in particular, that SNRs are not the sources of the CR nuclei as well. I believe that such conclusions stem rather more from an overly optimistic interpretation of the early models for the hadronic emission expected from these objects (Drury et al. 1994; Naito and Takahara 1994). As a consequence, now the disappointment is equally exaggerated.

Cassiopeia A is a somewhat different case (Fig. 14). In contrast to the two previous objects it is a γ-ray point source for all practical considerations. Physically it is a quite nonuniform source as judged from radio observations. In fact, Cassiopeia A is believed to be the result of an explosion into the nonuniform wind structure of a Wolf-Rayet star progenitor that went through several very different mass loss phases. Detailed modeling of the observed radio and X-ray synchrotron spectra, and of the resulting electron Bremsstrahlung and Inverse Compton emissions from this high density object is again consistent with an electronic origin of the γ-ray emission. On the other hand, one can make plausible estimates of the CR nucleon density in this remnant and they suggest a strong hadronic γ-ray component of the same order. From Fig. 14 the estimated electronic spectrum falls off rather strongly with energy already at 1 TeV, whereas there is no obvious reason for the hadronic spectrum to follow this behavior. Yet the observational spectral index estimate has a sufficiently large statistical error so that no statistically significant exclusion of an electronic origin of the γ-ray emission is possible from such arguments.

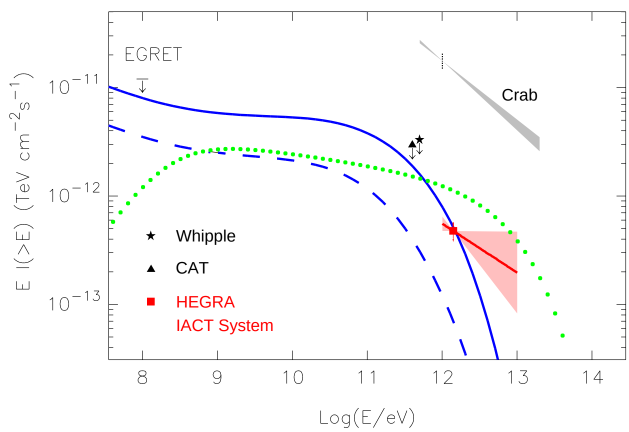


Fig. 14. The HEGRA γ-ray flux from Cassiopeia A (Aharonian et al. 2001a), together with the upper limits from EGRET on the one hand and the Whipple and CAT Cherenkov telescopes on the other, in relation to several model calculations. The solid and dashed curves show the electronic spectrum for two different sets of parameters; the dotted curve is an estimate for the hadronic spectrum. The observed spectral index of the HEGRA flux is similar to that for the Crab Nebula spectrum, within the indicated large 1σ uncertainty.

A refinement of the theory in terms of time-dependent kinetic solutions, simultaneously for electronic and hadronic emission, gives for SN 1006 comparable hadronic and Inverse Compton emission. A distinction will require a measurement of the γ-ray energy spectrum at high energies $0.1 \lesssim E \lesssim 10$ TeV, i.e. above and below the expected Inverse Compton cutoff. For Cassiopeia A, a similar spherically symmetric acceleration calculation results in a sizeable overproduction of hadronic γ-rays at 1 TeV. This could have several reasons, all connected with the poorly known circumstellar environment of the explosion site. Only spectroscopic measurements will help to unravel its dynamical structure.

6.2 The case of Tycho's Supernova

In the Northern Hemisphere Cassiopeia A is the brightest Galactic shell-type SNR at radio wavelengths. And it is the youngest one known, with an age of about 320 years. A seemingly much simpler object in our close vicinity is the remnant of Tycho's Supernova from 1572 A.D. The progenitor is thought to be an accreting White Dwarf - finally pushed over the Chandrasekhar limit- in an otherwise rather uniform Interstellar Medium. It is also not dominated by nonthermal electrons, showing instead a rich X-ray line spectrum. Thus it looks like an excellent candidate for hadronic γ-ray emission, at least for energies above 1 TeV, never mind a possible Inverse Compton component.

In a rather deep observation with the HEGRA telescope system, Tycho was not detected (Fig. 15). However, the upper limit on the TeV flux is essentially near the predicted hadronic flux from spherically symmetric kinetic theory, if this prediction is renormalized to the expected reduction of the injection efficiency for a remnant in a uniform external magnetic field. A ten times more sensitive instrument should readily detect it, unless the theory is wrong.

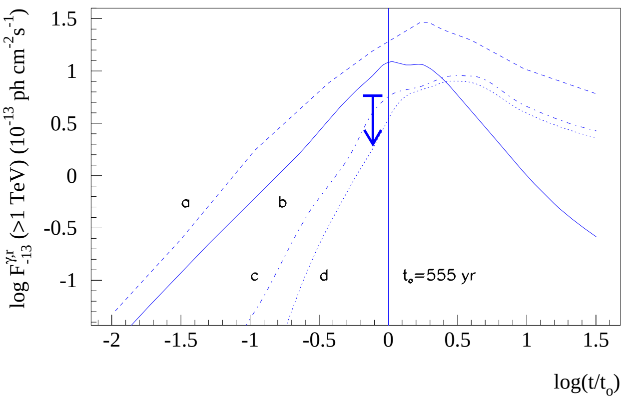


Fig. 15. The predicted TeV γ-ray flux from Tycho's SNR as a function of age, renormalized by a factor $1/3$, for various assumptions (a), (b), (c) about the nucleon injection rate into the acceleration process at the outer SNR shock, and stellar ejecta velocity distribution (d), together with the HEGRA upper limit (Aharonian et al. 2001b). The favored case (c), corresponding to the injection of 1 in 10^4 of the incoming upstream nuclei, lies closely above the observational upper limit.

6.3 Conclusions

What conclusions should we draw from this discussion? I would like to summarize them in four points:

1. There are less than a handful of direct shell SNR source detections up to now and they need to be confirmed. In particular the spectral information is still insufficient.

2. Theoretical models of diffusive shock acceleration are consistent with a roughly equal mixture of π^0-decay and Inverse Compton fluxes at energies around 1 TeV. Present γ-ray observations are not in contradiction with theory. The object Cassiopeia A must be considered a special case due to its complex circumstellar dynamics.

3. At present there exists a tantalizing observational uncertainty about the hadronic γ-ray fluxes. However, this uncertainty should be removed by the generation of experiments presently under construction, one way or the other. The capabilities on the ground (at high energies $\gtrsim 50\,\mathrm{GeV}$) and in space (at lower energies, up to some tens of GeV) will allow morphological studies of nearby extended SNRs. In combination they will give γ-ray spectral coverage up to $\sim 10\,\mathrm{TeV}$. Inverse Compton emission will either be harder than any conceivable hadronic emission, or it will have a comparable spectral slope but a low cutoff. In addition the number of detected sources should increase by an order of magnitude, giving statistical weight to these distinctions.

4. Nevertheless, the result might not prove the SNR source hypothesis. And then we would have to ask ourselves the difficult question, where we should turn to. Presumably only the much less well-understood Galactic jet sources would be left: X-ray Binaries, Microquasars, or even Galactic gamma-ray bursters. It is hard to imagine a more interesting and challenging situation for CR physics!

7 Diffuse Galactic gamma-ray emission (Transport)

Let me now come to CR propagation in the Galaxy, i.e. the transport properties of the nonthermal Interstellar component and to discuss two unexpected features of the Galactic emission that have been discovered some years ago. They are probably the main anomalies, given the limited spectral coverage and angular resolution of present instruments.

7.1 The GeV excess

Extensive observations with the satellites SAS-II, Cos B, and CGRO in the range above 100 MeV have shown that the γ-ray flux from the Galactic disk is to lowest order consistent with a uniform CR intensity there. This suggests effective spatial mixing, and is basically consistent with the idea that CRs are diffusively confined in a large, quasi-spherical Galactic Halo as put forward by the Moscow school (Ginzburg and Ptuskin, 1976). Such a measure of uniformity for the CR density above 100 MeV suggests a rather uniform shape of the CR energy spectrum as well. However, the EGRET instrument has found a hard γ-ray spectrum $\propto E^{-2.4}$ at energies above 1 GeV which is in clear excess of the predicted spectrum $\propto E^{-2.75}$, based on the locally observed CR nucleon spectrum.

Unexpected as it was, this discrepancy has raised a number of questions:

(i) Is the local CR nucleon spectrum not really representative for the rest of the Galaxy on a large scale?

(ii) If this is indeed not the case, should we then for instance think of an additional Inverse Compton emission from the neighborhood of external sources of CR electrons?

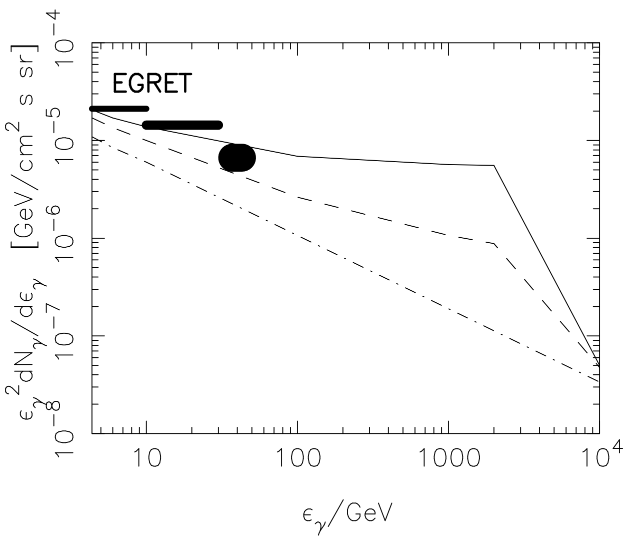


Fig. 16. Integral diffuse γ-ray energy flux in the Galactic disk (EGRET data from Hunter et al. 1997). The dash-dotted line is a model based on the locally observed CR flux, whereas in the solid curve a purely theoretical, and in the dashed curve a more realistic phenomenological SNR source flux is added to this model flux. The fall-off beyond ~ 2 TeV is due to the assumed escape of $\gtrsim 20$ TeV CRs at late stages of source evolution (from Berezhko and Völk 2000).

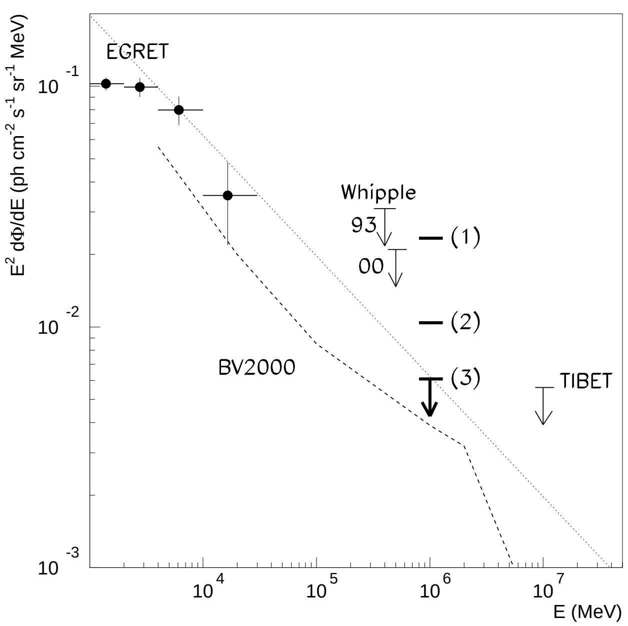


Fig. 17. Integral diffuse γ-ray energy flux in the inner Galactic disk together with TeV upper limits from several experiments compared to the scaled prediction (cf. the dashed curve in Fig. 16), that includes unresolved SNR sources. The lowest upper limit (3), from the HEGRA experiment, is quite close to the model prediction (from Aharonian et al. 2001c).

(iii) Do we have to expect a substantial contribution $\propto E^{-2.1}$ from the ensemble of unresolved CR sources?

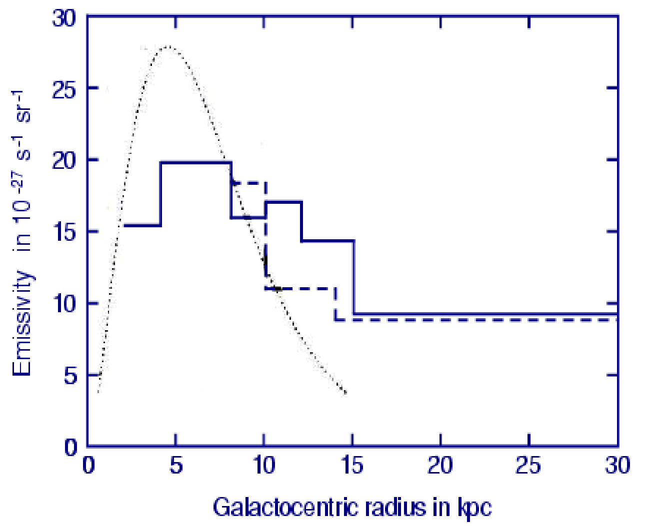


Fig. 18. The γ-ray emissivity in the EGRET energy range as a function of Galactocentric radius (solid and dashed histograms) in comparison to the (dotted) SNR distribution as seen at radio frequencies (from Paul 2000).

Alternative (i) implies that along the γ-ray line of sight the nucleon spectrum is different from the local one, possibly due to propagation effects during escape. Given the fact that in a Galactic Wind convection becomes stronger relative to diffusion with increasing height above the disk midplane, most line of sights through the disk should indeed include a hard-spectrum convective contribution.

As to the second question, it is true that high energy CR electrons can propagate only over a rather limited range in the face of radiative losses. Therefore, if the Solar system is not very close to a source, our local electron spectrum may not be really representative at these higher energies and possibility (ii) might contribute.

Perhaps the most interesting alternative is (iii). The estimated hard-spectrum contribution of an unresolved SNR source distribution to the "diffuse" γ-ray background in the disk is still small at 1 GeV but finally dominant at TeV energies (Fig. 16). Thus the SNR sources should "stick out" at high energies $E \sim$ TeV. Fig. 17 shows the latest measurements of the TeV γ-ray background deep in the disk. Even though not detected yet, its upper limit lies less than a factor 2 above the expected flux. A clearly detected energy spectrum for $0.1 \lesssim E \lesssim 1$ TeV should in the future allow a direct measurement of the average CR source spectrum in the TeV range by the subtraction of a model flux based on the locally observed CR nucleon spectrum from this diffuse spectrum!

Of course these alternatives are neither exclusive nor exhausting all possibilities. For example, at energies $<$ 100 GeV the unresolved source scenario could possibly still accomodate an additional hard-spectrum component. However detection of angular fluctuations in the hard γ-ray spectrum would at least separate the systematic effect (i) from the

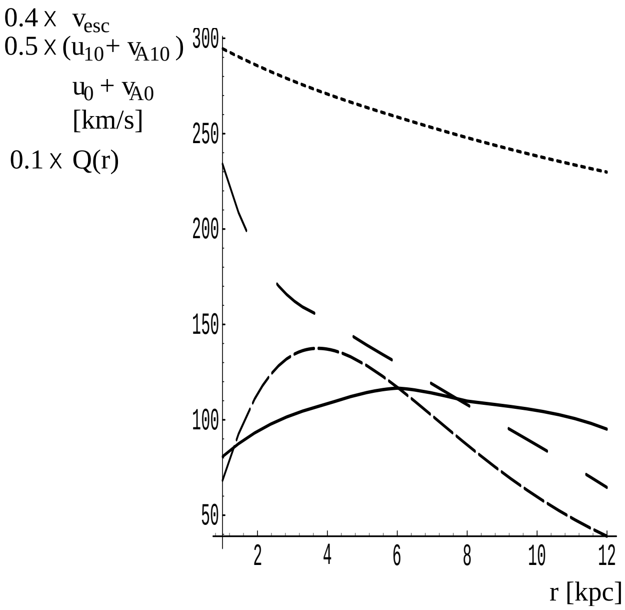


Fig. 19. Escape speed v_{esc} (dotted line) and CR drift velocity $u_{10} + v_{A10}$ (long dashed line) at the large height of 10 kpc above the disk as a function of Galactocentric radius r; both fall off radially due to the fall-off of the overall Galactic gravitational potential distribution. The drift velocity $u_0 + v_{A0}$ (solid line) at the energy-averaged diffusion/convection boundary of the Galactic Wind at $\lesssim 1$ kpc is more strongly influenced by the peak of the SNR distribution, assumed to be proportional to the CR source distribution (short dashed line). The source peak produces a maximum in u_0+v_{A0} as a function of radius and thus counteracts the CR density enhancement in a steady state (from Breitschwerdt et al. 2001).

other two. Ultimately, the detailed spectral investigation of a resolved background will be able to distinguish cases (ii) and (iii).

7.2 The average radial gamma-ray gradient in the Galaxy

There is a second puzzling feature in the diffuse γ-ray emission from the Galactic disk. At GeV energies the radial Galactocentric γ -ray emissivity gradient is too small to be explainable by uniform CR diffusion from the SNR sources, which are assumed to lie in the disk (Fig. 18). This might be interpreted as an argument against a CR origin from massive stars in the disk since they are strongly concentrated in the 4 to 6 kpc molecular ring around the center of the Galaxy. However, CR propagation away from the Galaxy should actually be a strongly nonlinear process, determined by the dynamical effects of the escaping CRs themselves. We must indeed expect that the CRs from a large scale concentration of sources drive a faster Galactic Wind from these sources by their enhanced pressure. This enhanced removal rate counteracts the increase in the particle source strength in a self-regulating manner (Fig. 19). Thus, spatial uniformity of CRs does not need to be exclusively due to their diffusive nature, but as well due to the inability of the Interstellar gas to weigh them down. Although considered here as an effect along magnetic flux tubes directed away from the disk, such a behavior is basically the result of a force balance requirement between gas, field and CRs, including the gravity due to the stars.

An attractive feature of such a proposal is that it can be readily tested by the detection of the diffuse γ-ray background in the TeV range: the ensemble of unresolved CR sources should become visible directly at these γ-ray energies, reconstituting the radially peaked SNR distribution that is so clearly seen at radio frequencies.

8 Main forthcoming gamma-ray detectors

The next years will see a number of new γ-ray detectors which are expected to resolve the questions adressed in the two previous sections. The main projects are the Gamma-ray LArge Satellite Telescope (GLAST) and several large ground-based telescopes. They are expected to put high energy γ-astronomy on an entirely new level of flux sensitivity and wavelength coverage with new classes of sources detected. Using the known gas density structures, especially the distribution of Giant Molecular Clouds, the instruments should also be able to map the diffuse CR density and energy distribution in the Galaxy in full detail.

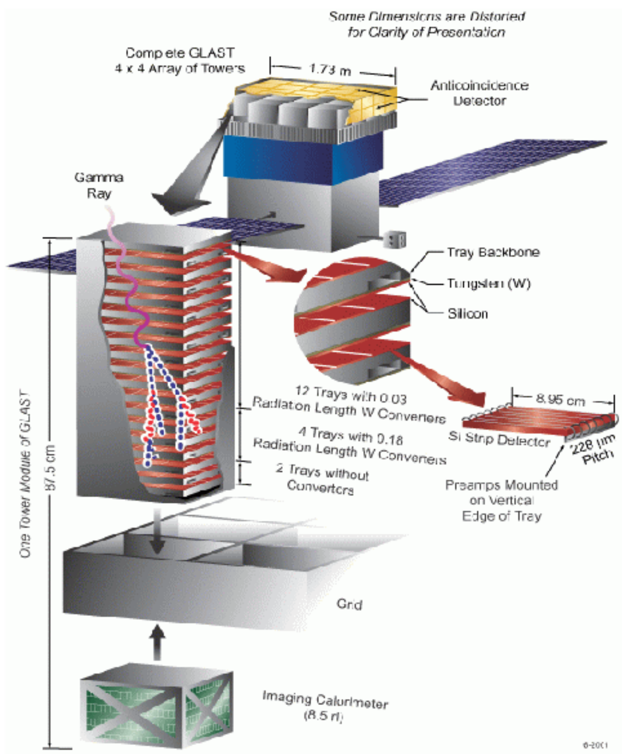


Fig. 20. View of the GLAST instrument and its various detectors. The scheme consists of a 4×4 array of so-called towers which contain converters for γ-rays together with silicon trackers for the electron/positron pairs, followed by an imaging calorimeter.

NASA plans to launch GLAST in 2006. The instrument is based on silicon strip detectors and will have a much im-

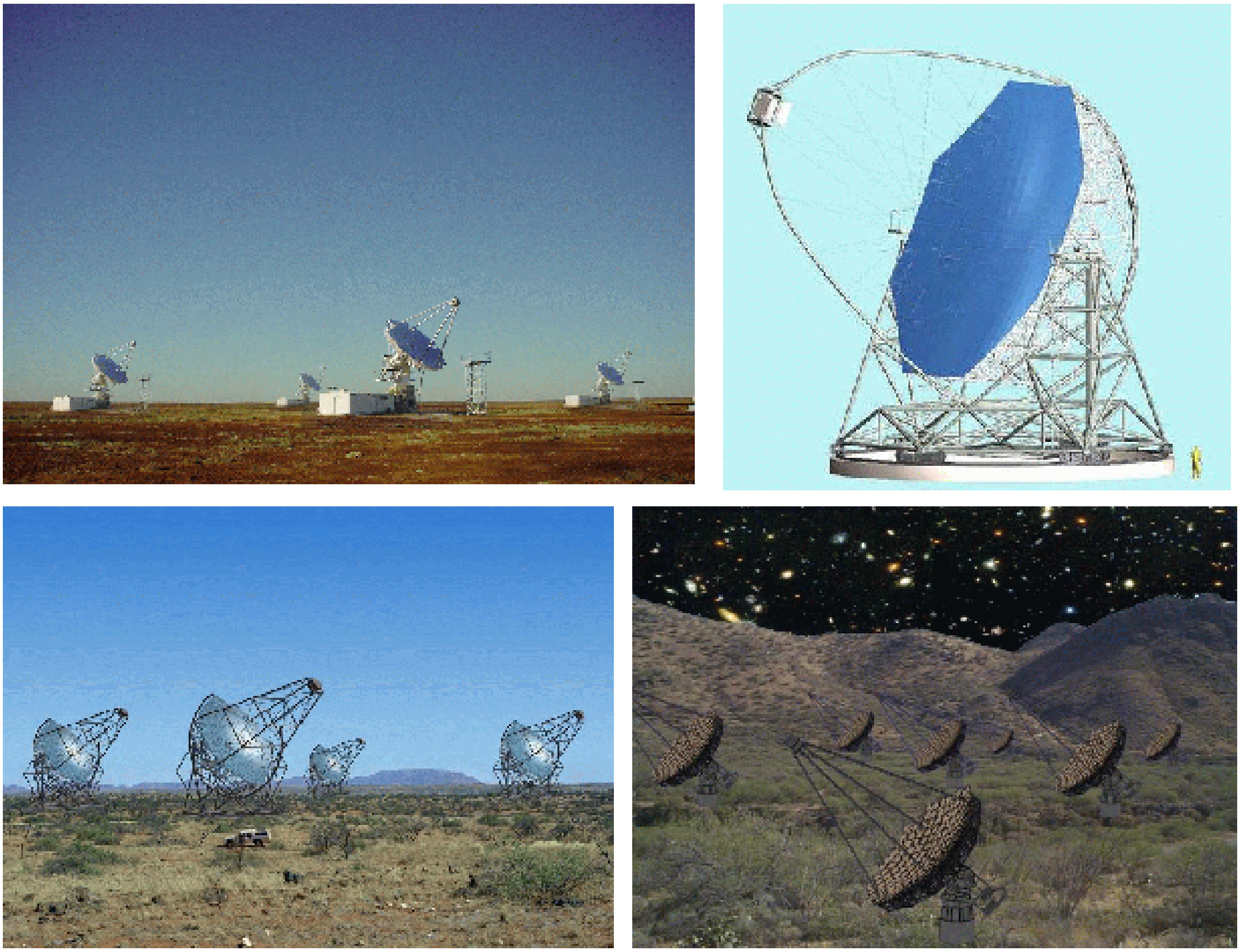


Fig. 21. Photomontages/schematics of the main new Cherenkov telescopes. From the upper left to the lower right: the CANGAROO-III system of 4 telescopes (one telescope already in operation), the MAGIC telescope (Major Atmospheric Gamma Imaging Cherenkov telescope), the 4-telescope Phase I of H.E.S.S. (High Energy Stereoscopic System), and the 7-telescope array of VERITAS (Very Energetic Radiation Imaging Telescope Array System).

proved angular resolution compared to EGRET - now matching that of the best ground based instruments - and strongly increased sensitivity up to at least 100 GeV. At the higher energies this sensitivity jump will in many regards remain rather limited by statistics, because of the size restrictions on a detector operating on a satellite. In any case GLAST is expected to survey the sky very effectively at lower energies due to its large field of view, complementary to the higher threshold ground based arrays of telescopes whose major aim will be pointed observations.

Four such large Cherenkov telescopes are under construction: CANGAROO III in Australia, H.E.S.S. in Namibia, VERITAS in the U.S.A., and MAGIC on the Canarian Island of La Palma (Fig. 21). The first three detectors are stereoscopic systems like HEGRA, with telescope diameters of the order of 10 m, whereas MAGIC is a 17 m diameter single telescope. The energy thresholds are expected to lie between 30 and 100 GeV, and they will be roughly an order of magnitude more sensitive than present instruments at $E \sim 1$ TeV. The first telescope of CANGAROO III is already in operation, H.E.S.S. and MAGIC are expected to see first light in early 2002, and VERITAS plans for first light in 2003.

8.1 The H.E.S.S. experiment in Namibia

In conclusion let me say a few words about the H.E.S.S. array as a representative example of the new ground based instruments. The name H.E.S.S. is an acronym for *High Energy Stereoscopic System* and was chosen in honor of Victor Hess.

The H.E.S.S. array[4] is designed for coincident stereoscopic observations with several telescopes. Phase I of the experiment consists of four 13 m diameter telescopes, at the corners of a square whose sides are ≈ 120 m in length, roughly corresponding to the radius of the Cherenkov light disk on the ground. The scientific collaboration involves about 60 individuals from European and Southern African

[4] Detailed information on the experiment is to be found at the Web site: http://www.mpi-hd.mpg.de/hfm/HESS/HESS.html.

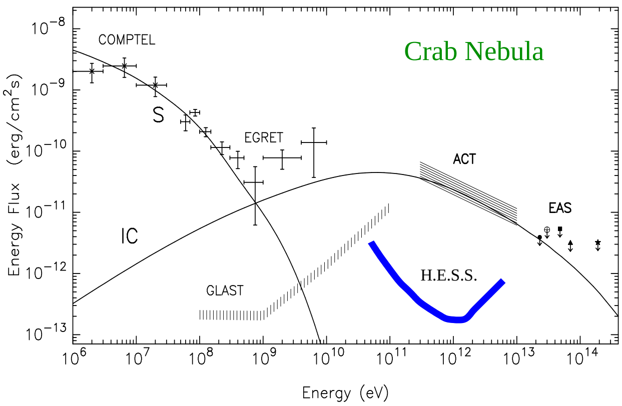


Fig. 22. Performance of H.E.S.S. Using existing measurements of the Crab Nebula together with model curves, for the spectral range $\lesssim 10^9$ eV (synchrotron radiation) by the CGRO instruments COMPTEL and EGRET, and for the range $\gtrsim 10^{11}$ eV (Inverse Compton (IC) radiation) by imaging atmospheric Cherenkov telescopes (ACT), as well as upper limits from extensive air shower (EAS) arrays, the H.E.S.S. Phase I sensitivity for 50 hours of observation is plotted as a function of γ-ray energy. It is also compared with the expectations for the GLAST instrument.

institutions. The scientific and official Namibian collaboration partner is the University of Namibia in Windhoek. The first telescope should become operational by the beginning of 2002, the full Phase I system in 2003. H.E.S.S. is a natural extension of the HEGRA stereoscopic system on La Palma and of the imaging technique in the CAT telescope in the French Pyrenees.

Fig. 23. Section of a map of Namibia in southern Africa. The H.E.S.S. site (Göllschau) lies about 90 km southwest of Windhoek.

The H.E.S.S. telescopes will have a comparatively large field of view of 5 degrees. Their energy threshold lies

Fig. 24. Steel frame of the first H.E.S.S. telescope. Rotation around the vertical axis is on a circular rail of ~ 15 m diameter.

at $\approx$ 50 GeV for the detection of a source, and at $\approx$ 100 GeV for spectroscopic and spatially resolved observations. The angular and energy resolutions per event are estimated as 0.1 degrees, and 10 to 20 percent, respectively. The lowest energy flux detectable in 50 hours of observation time is about 10^{-12} erg/(cm^{2}s) above 100 GeV, and about

Fig. 25. The first H.E.S.S. camera frame at the University VI – VII in Paris, in spring 2001 (with J.-P. Tavernet standing in front). At this stage the camera was partly equipped with photomultipliers and the corresponding electronics in the back. In full configuration the camera has a total number of 980 phototubes (pixels) and a weight of about 860 kg.

10^{-13} erg/(cm^2)s above 1 TeV (Fig. 22). Therefore the hope is to find new source populations whose TeV fluxes are about hundred times lower than that from the Crab Nebula.

The site in Namibia is located in the Khomas Highland at 1800 m above sea level. Geographically this is almost precisely on the tropic of Capricorn, near the famous Gamsberg table mountain on a 10 km^2 piece of farm Göllschau (Fig. 23). It can be reached on a good dirt road from the capital city of Windhoek in about 1.5 hours. The Gamsberg area is one of the best optical sites in the world and the mountain itself had been considered as a possible site for the European Southern Observatory's Very Large Telescope project that is now on Cerro Paranal in Chile.

In the region cattle shares the scarce grass and water with occasional Kudus and Antilopes. The steel frame of the first telescope is shown in Fig. 24. The 380 glass mirrors of 60 cm diameter each, and finally the focal plane detector (the "camera", Fig. 25) are due to be put on this frame in fall of this year. Scientific operations of the telescope are expected to start in early 2002 if all goes well.

Acknowledgements. I thank Alexander Konopelko for his comments on the manuscript.

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