Physics Results and Physics Potential of Ground-Based γ-ray Astronomy

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Abstract

Since the discovery of the Crab nebula as an emitter of very high energy γ-rays in 1989, ground-based γ-ray astronomy has opened a unique window to the high energy physical proceses occuring in the near and distant universe. Some recent physics results will be presented. Currently a new generation of Imaging Air Cherenkov Telescopes is under construction in several locations on the northern and southern hemisphere. Based on the expected performance of the MAGIC Telescope a significant enhancement of the physics prospects of ground-based γ-ray astronomy is indicated.

Key words: VHE gamma rays, Active Galactic Nuclei, Cherenkov telescope

1 Introduction

Gamma-ray astronomy is the most recent addition to the spectrum of 20th century astronomy. This concluded the opening of the *complete* electromagnetic spectrum to astronomical observations. Currently γ-ray astronomy is performed by space-borne and ground-based γ-ray detectors in non-overlapping energy domains. The space-borne detectors measure in the energy domain up to $\sim$10 GeV whereas the ground-based detectors are limited to photon energies *above* $\sim$200 GeV. The remaining gap in the electromagnetic spectrum will be closed by the upcoming detectors from both sides, i.e., by the ground-based and space-borne detectors enlarging their energy coverage. Here we only

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report on some recent results from ground-based γ-ray astronomy, i.e., results obtained with Imaging Air Cherenkov Telescopes (IACTs) (1).

The main objective of γ-ray astronomy is the study of astrophysical objects or phenomena characterized by non-thermal emission spectra. In some prominent of the identified sources the central rôle in the production of very high energy photons is played by compact massive objects, i.e. Neutron stars, stellar mass Black Holes or Supermassive Black Holes with masses ranging from about 10^6 to 10^{10} solar masses. The latter identifications are based on the tremendous energies released by the most violent γ-ray sources in the universe, Gamma-Ray Bursts (GRBs) and Active Galactic Nuclei (AGN). For GRBs the event itself might be the real time signal of the gravitational collapse to a stellar mass Black Hole, and for AGN the observed energetics calls for central gravitational potentials corresponding to massive objects with masses of the order of a tens of a percent of the host galaxy bulge mass. The depth of the potential wells leads to relativistic motions of particles deep within these wells. These particles constitute the **relativistic universe** characterized by very high observed luminosities and particle energies where in both cases the effects of relativistic beaming have to be taken into consideration when modelling the sources. The emission processes relevant for relativistic source particles naturally produce the above-mentioned characteristic signature of the relativistic universe, i.e. non-thermal or power-law like spectra.

Very high energy (VHE, i.e. $E > 100$ GeV) γ-ray astronomy can only be performed by ground-based installations due the low and steeply falling fluxes from most conceivable γ-ray sources and the strongly limited size of space-borne detectors. Up to 1989 the VHE γ-ray sky contained no identified source with more than 5 σ significance due to lack of sensitivity of the employed instruments. Following the detection of the Crab Nebula as a source of γ-radiation at energies above 500 GeV by the Whipple collaboration in 1989 (2), up to now 13 sources of VHE gamma-radiation have been identified, 6 AGN, 3 shell-type SNRs, 3 plerion-type SNRs and 1 binary system. Four of these sources have been detected with certainty, while the other 9 have been detected by individual groups and possibly at times of outburst and need further confirmation (3).

2 Galactic Sources

2.1 The Crab Nebula

The Crab nebula is the supernova remnant (SNR) of a supernova observed in 1054. It is a plerion type SNR, i.e. a central pulsar continuously injects electrons into the nebula which are then shock accelerated to high energies. The emission from the radio to X-rays is supposed to originate from synchrotron emission of these electrons in the magnetic field of the remnant. The synchrotron flux is a function of the field strength and the electron density. As the synchrotron components of different wavebands overlap the field strength can not be determined from the synchrotron spectrum alone. In the Crab nebula the magnetic field strength is such that inverse Compton (IC) scattering on low energy photons occurs at a measurable rate. The measurement of the two spectral components then allows to measure the field strength and the total energy contained in the high energy electron population. Assuming that the soft 'target' photons for the inverse Compton scattering are the synchrotron photons emitted by the same electron population that upscatters the soft photons (Synchrotron self-Compton model) the IACT data above $\sim$300 GeV allowed the magnetic field to be determined to be $1.6 \pm 0.1 \times 10^{-4}$ G (4). The energy spectrum up to 20 TeV was determined by the HEGRA experiment and found to be in good agreement with a pure power-law and in good agreement with the expectation for a pure IC component (5). A possible hard hadronic component as expected from the production of secondary π^0s if hadrons are also accelerated to very high energy energies in the Crab nebula could not be identified at these energies. If present it is expected to show up at energies beyond $\sim$30 TeV.

2.2 Shell-type Supernova Remnants

Shell-type SNRs are commonly believed to be the sources of the hadronic Cosmic Rays roughly up to energies corresponding to the knee in the all-particle spectrum, i.e. $\sim 10^{15}$ eV (see e.g. (6)). As the hadronic Cosmic Rays do not retain any directional information due to deflections in the galactic magnetic fields, γ-rays produced in the decay of secondary π^0s are searched for as signal for the presence of very high energy hadrons interacting with target hadrons, e.g. within dense molecular clouds in the vicinity of the SNR. The VHE γ-ray luminosity is expected to be particularly high for those shell-type SNRs which are in the Sedov phase, i.e. which have swept up as much mass in form of interstellar material as contained in the SN ejecta (7).

Up to now 3 shell-type SNRs (SN1006, RJX1713.7-3946, CasA(with 4.5.σ significance)) have been identified as VHE γ-ray emitters by the CANGAROO (8), (9) and HEGRA experiments (10), respectively. In addition a number of upper limits on the VHE γ-ray fluxes from shell-type SNRs have been published (see e.g. (11)). The observed VHE γ-ray signals have yielded clear evidence for particles being accelerated to energies of the order of 100 TeV. So far, however, the observed signal strengths and spectral shapes are compatible with only electrons being accelerated in these remnants. To identify a possible hadronic, i.e. π^0, component more data and especially spectral information will be needed. To conclude, the sources of the hadronic Cosmic Rays have not yet been identified.

3 Extragalactic Sources

The most spectacular discoveries in ground-based γ-ray astronomy are related to the *extragalactic* sources of VHE γ-rays. The first such source discovered in 1992 by the Whipple collaboration (12) was the closest BL Lacertae (BL Lac) type object Markarian 421 (Mrk 421) at a redshift $z = 0.031$. This AGN at the same time is one of the weakest γ-ray source detected by the EGRET experiment at energies below $\sim$10 GeV (13) and showed the shortest time variations of its γ-ray emission levels observed so far with doubling and decaying times in the energy domain above $\sim$200 GeV as short as 15 minutes (14). The amplitude ratios between the discovery flux level and flux maxima during short outburts have been as large as 30, i.e., between 0.3 and 10 Crab, where 1 Crab is the (time-independent) flux of the standard candle of γ astronomy, the Crab nebula.

BL Lac objects and flat spectrum radio-loud quasars (FSRQs) are collectively called "blazars". The predominantly non-thermal emission shows violent variability in most energy bands and superluminal motion is observed in VLBI[2] radio surveys. The non-thermal emission is believed to originate in relativistic jets oriented with small angles towards the line of sight. The emission levels and time scales observed in the TeV domain, e.g., for Mrk 421, clearly show that *relativistic beaming* has to be operational in the sources, corroborating this model picture. The ultimate energy source is believed to be gravitational, i.e., originating from accretion of matter onto a supermassive (O(10^8 - 10^9) $M_\odot$) black hole in the centre of the AGN.

The second extragalactic source, Mrk 501, was discovered in 1995 (15) as a weak source (0.08 Crab). In the beginning of 1997 it showed a dramatic outburst at TeV energies which lasted for the full 1997 observation period (March - September) and was characterized by wildly varying emission levels. The most complete light curve at energies larger than 1.5 TeV was obtained by the 6 IACTs of the HEGRA collaboration who operated at that time a stereoscopic system of 4 IACTs and 2 additional stand-alone telescopes. In order to achieve this good time coverage of Mrk 501 for the first time measurements during moon time were performed with one of the stand-alone telescopes (CT1) (16). This observation mode considerably increased the time coverage with only a moderate increase in energy threshold. The light curve measured

[2] Very Long Baseline Interferometry

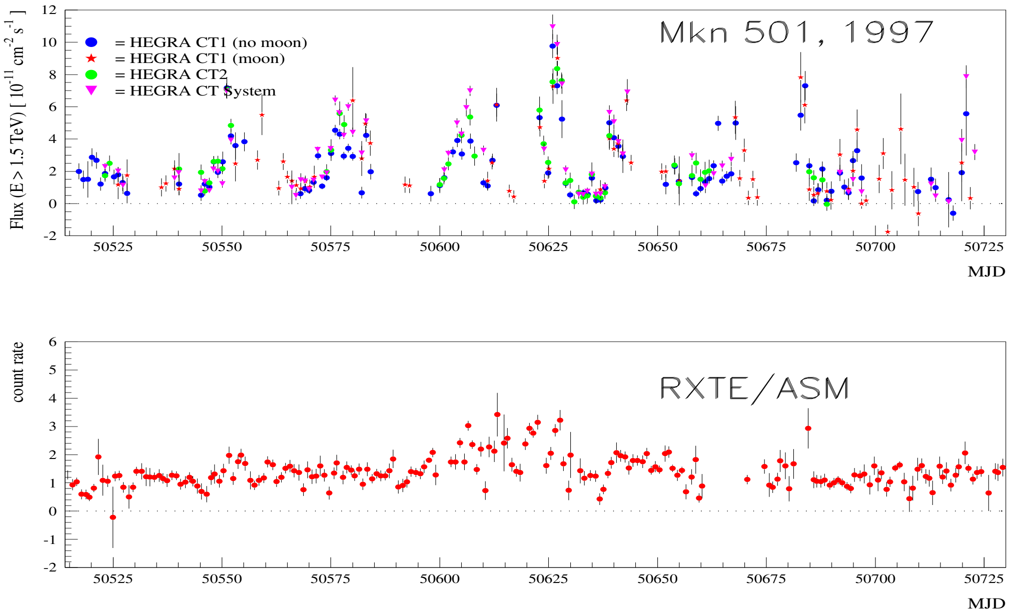

Fig. 1. Light curves of Mrk 501 in 1997. Top: VHE γ-ray (> 1.5 TeV) emission measured by the HEGRA IACTs. Modified Julian Day 50449 corresponds to January 1, 1997. Bottom: X-ray light curve measured by the RXTE ASM for 2 keV $\leq$ E $\leq$ 10 keV. From (18).

by all HEGRA IACTs is depicted in figure 1 (top diagram). Concurrently with HEGRA and many other IACTs (e.g., (17)) the Allsky Monitor (ASM) of the RXTE X-ray satellite took data on Mrk 501 in the 2 to 10 keV energy band. The corresponding light curve is also shown in figure 1 (bottom diagram). HEGRA performed a correlation analysis and found a moderate (0.611 ± 0.057) but clear ($8.5\ \sigma$) correlation between the TeV and keV emission levels (18) indicating a common emission region of the radiations.

HEGRA investigated the X-ray and TeV light curves shown in figure 1 for quasi-periodic oscillations (QPOs) (19). In the QPO analysis evidence for a 23 day period was found in both light curves. In order to assign a statistical significance a shot noise model assuming as null hypothesis independent, randomly distributed flares in accordance with observations was developed (20). The combined probability for the 23 day period was thus determined to be P = 2.8 e-04 or 3.5σ. Note that this analysis was only possible because the data taken during moon time were available. Leaving out these data introduces large time gaps and the observed QPO signal will be washed out due to the introduction of aliasing effects.

Besides the light curve the other important measurement concerns the γ-ray energy spectra of AGN during high and low states. The most striking aspect of the HEGRA energy spectrum of Mrk 501 in 1997, besides its independence from the flux level, is the maximum energy observed from this source. This energy spectrum together with the energy spectrum determined for Mrk 421

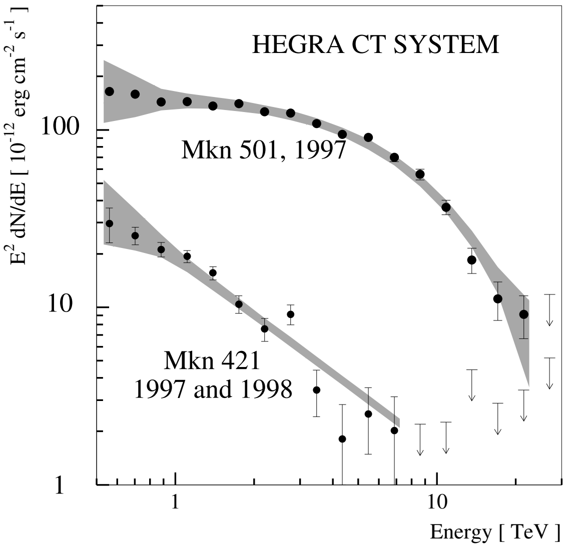

Fig. 2. The energy spectra of Mrk 421 (1997 and 1998 combined) and Mrk 501 (1997) as measured by the system of HEGRA IACTs. From (21).

from the combined 1997 and 1998 data is shown in figure 2. The 95% CL lower limit on the maximum detected energy from this extragalactic source is 16 TeV! Due to the distance of Mrk 501 of about 500 million light years the measurement of this maximum energy is a cosmologically important signal. The reason for this is that the TeV γ-rays have to traverse the diffuse extragalactic background light (EBL) in order to arrive at the location of our Galaxy. The EBL constitutes an important cosmological signal as it integrates over the emission history of the Universe on Hubble time and length scales. Important parts of the EBL spectrum, amongst others the infrared region, however, are still only known very poorly from direct measurements by satellite detectors. TeV γ-rays can interact with infrared photons to produce electron-positron pairs. A large density of diffuse infrared photons therefore results in measurable absorption features in extragalactic γ-ray spectra. As the energy dependence of the EBL flux is roughly $\propto$ E^{-1} *quasi-exponential* cutoffs of the TeV spectra are expected. By turning this argument around one sees that a beam of TeV γ-rays traveling cosmological distances can be used to *probe* this background field. As the relevant Thomson cross section is strongly peaked at the threshold this probing can even be performed spectroscopically by observing sources at different distances. Because of the energy dependence of the EBL spectrum the cutoff condition, i.e., optical depth reaching unity, for sources at different cosmological distances occurs at different γ-ray energies. This should result in a 'cosmological γ-ray horizon' with the Universe opening up as one goes towards lower γ-ray energies. A small fraction of the EBL spectrum is shown in figure 3. A striking feature is that in the shown energy interval between the far infrared ($\sim$200 μm) and the ultraviolet (UV) ($\sim$0.1 μm) the figure is dominated by wildly scattered upper and lower limits. The main reason for this is the enormous foreground radiation in this spec-

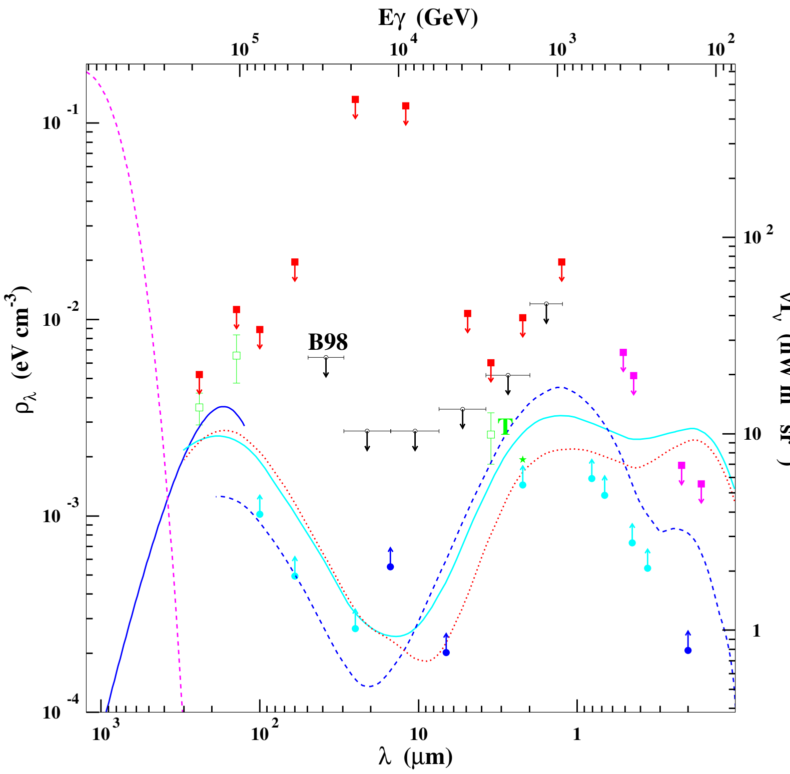

Fig. 3. The density of the EBL between the far-infrared and the ultraviolet. Filled squares with arrows indicate 95%CL upper limits by various experiments. Open squares are detections (140 and 240 μm) and a tentative detection (3.6 μm, denoted by T) by DIRBE. The filled circles are lower limits from IRAS and ISO galaxy counts. For references see (22). The horizontal bars with arrows indicate the upper limits from the Mrk 501 spectrum derived in (23). The dashed line above 300 μm indicates the level of the 2.7K CMB. The dotted and dot-dashed lines are model predictions from (24) and the dashed line a prediction taken from (25). The top scale denotes the VHE γ-ray energy corresponding to the peak in the absorption probability on the EBL due to $\gamma\gamma \rightarrow e^+e^-$. From (22).

tral range by the zodiacal light in our solar system. Besides the limits and measurements obtained with 'direct' methods also the upper limits on the IR EBL level derived from the TeV γ-ray spectrum of Mrk 501 as measured by the Whipple collaboration is shown in figure 3. A similar analysis was performed on the basis of the HEGRA data resulting in an upper limit of 1.1×10^{-3} eV/cm^3 at $\sim$25 μm *assuming* a specific shape of the IR background (26). As visible in figure 3 the application of the methods of TeV γ-ray astronomy have already led to an improvement of the upper limits in the mid-infrared range by more than an order of magnitude. Especially in the mid-infrared range where the models predict a pronounced dip in the diffuse extragalactic photon flux the dominating foreground will also in the future probably not allow a certain direct determination of the flux level by infrared satellites. The level of the EBL in this range, however, is an important signal of structure formation in the Universe and constitutes a (complicated) convolution of star formation rate, initial mass function and its evolution, and the dust history of the Universe. It is therefore of paramount interest to determine the flux with the methods of TeV astronomy. As this means measuring cutoff energies in the TeV domain, it makes it necessary to find more close-by (on cosmological scales) TeV sources, i.e., raising the instruments sensitivities as planned for the next generation of γ-ray detectors.

4 Physics Potential of the MAGIC Telescope

A prominent example of such a next generation γ-ray detector is the 17 m diameter MAGIC Telescope currently being constructed on the Canary Island La Palma. It will be significantly larger than other planned installations and can thus address a number of unique physics questions (see e.g. (27)).

The main performance parameters of the MAGIC Telescope leading to a significant improvement in the physics capabilities are the very low energy threshold, the very large effective collection area and the very good sensitivity. In addition it will have a fast data aquisition system and a fast slewing capability. The main physics questions which will be addressed with this instrument are from the fields of cosmology, astrophysics and particle physics and can be summarized as

- Cosmology:
  - can the diffuse γ-ray background be resolved into sources?
  - the determination of the cosmological γ-ray horizon
- Astrophysics:
  - what are the sources of the hadronic Cosmic Rays?
  - the study of Active Galactic Nuclei
  - what is the emission process responsible for γ-ray bursts?
  - what is the γ-ray emission process for γ-ray pulsars?
- Particle Physics
  - testing Lorentz Invariance
  - search for annihilation of non-baryonic Dark Matter particles

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