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Recent Status of High-Energy Gamma-Ray Astronomy

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Abstract. Sub-TeV and TeV energy gamma-ray astronomy reveals non-thermal gamma-ray pictures of our universe and serve as a probe to understand the origin, acceleration and propagation of cosmic rays. Recent status of ground-based high-energy gamma-ray astronomy is reviewed.

1. Introduction

TeV gamma-ray astronomy aims at astrophysics as well as particle physics. The purpose is to understand the origin, acceleration mechanism and propagation mechanism of TeV gamma rays and physical source parameters, flux variability, to search for new source classes with expected TeV gamma-ray emission, to do observational cosmology, such as the determination of interstellar infrared photon background from gamma-ray attenuation and cascading, to search for dark matter, etc. In this review, only very limited topics are sampled from various observations and theories.

2. Detection Techniques

2.1. Air Cherenkov Detectors

A 1-TeV cosmic gamma ray interact with the atmosphere to initiate electromagnetic showers with cascading low-energy gamma-rays and approximately 1000 electrons and positrons at the shower maximum roughly 8 km in altitude. The electrons and positrons emit Cherenkov light photons within a light cone of approximately 1 degree. The signal on the ground is a few nanosecond long flash of light with a few 100 Cherenkov photons per m^2 in a light pool of 240m in diameter. Charged primary cosmic rays, the overwhelming background (a factor of >1000) also produce airshowers with electromagnetic subcascades. Based on statistical characteristics, hadronic events can be thrown out by means of their irregular shapes and directional information (angular resolution $\sim$0.2 deg). The imaging air Cherenkov telescopes (IACTs) in the world (Whipple, HEGRA, Cangaroo, CAT, Seven TA, Crimea, Shalon, Durham,Tactic) have energy thresholds of 0.25 to 1 TeV. Typically, an IACT is sensitive to the Crab gamma-ray flux at $5\ \sigma\sqrt{t}$/hour, or $10^{-12}/\mathrm{cm}^2/\mathrm{s}@1\mathrm{TeV}$ ($\sim$ 1/10 Crab).

Lower energy threshold Cherenkov detectors started (CELESTE, STACEE, GRAAL experiments) or is preparing (Solar-2 experiment)for operation. These detectors have a larger but sparse mirror areas utilizing existent solar heliostat mirrors. Secondary optics in the tower image Cherenkov light onto photomultiplier tubes. CELESTE detected the Crab and Mrk421 at high (7-8 σ) significance in 1999/2000 obsevations with an energy threshold of 60±20 GeV (de Naumois et al. 2002). STACEE also successfully observed the Crab at 7 σ significance in 1998/1999 with an energy threshold of 190±20 GeV (Oser et al. 2001). GRAAL also succeeded in detecting the Crab signal above 250±100 GeV at 4.5 σ significance (Arqueros et al. 2002)

In spite of the good sensitivity, air Cherenkov detectors can observe the sky only at moonless clear nights (10 % duty cycle typically) with a narrow field of view (a few degrees × a few degrees typically) .

2.2. Air shower arrays

Air shower arrays, having a lower sensitivity to gamma rays (5 $\sigma\sqrt{t}$/yr for Crab) than Cherenkov detectors, allows high duty cycle (~100 %), omni-weather and wide field-of-view (a few steradian typically). However, their angular resolution is moderate (~1 deg@1TeV). They are ideal for long-term monitoring of bright transient sources, for gamma-ray bursts, and for unknown bright constant sources. The 37000m^2 Tibet-III scintillator array at 4300 m a.s.l. in Tibet, China achieves an enery threshold of a few TeV. MILAGRO is a water Cherenkov experiment in U.S.A. with an energy threshold below 1 TeV. ARGO will be in operation in 2004 using resistive plate counters, next to the Tibet-III site in Tibet. The potential of these experiments is demonstrated by the successful detection of gamma rays from the Crab (Amenomori et al. 1999), Mrk501 (Amenomori et al. 2000) and Mrk421 (Amenomori et al. 2001) by the Tibet experiment, and by the possible detection of a gamma-ray burst GRB970417a by Milagrito (the MILAGRO prototype detector) (Atkins et al. 2000).

3. TeV gamma-ray sources

The current TeV catalog, composed of 16 sources. Six of them are confirmed, i.e., observed with high significance (>5 σ) by more than one group. The others are typically 5 to 7 σ detection by a single group. There are also intriguing upper limits on diffuse gamma rays from the Galactic plane (Amenomori 2002), pulsed emission from pulsars, and non-blazar type AGNs. Only a few of the sources will be picked up here.

3.1. Galactic Gamma-ray Sources

The Galactic sources are three plerions (Vela, PSR1706-44, Crab), three shell-type supernova remnants (RXJ1713.7-3946, Cas-A, SN1006) and one X-ray binary (Cen-X3). The Crab and PSR1706-44 are confirmed sources.

The "standard candle" in TeV astronomy is the Crab Nebula, the remains of a supernova explosion in 1054 AD. It was the first observed TeV gamma-ray source by the Whipple group in 1989, and is the brightest constant source known sofar. The present most sensitive instruments detect a few gamma rays per minute from the Crab. The energy spectrum from radio to TeV energies can be understood in the framework of synchrotron inverse Compton models, where electrons emitted from the pulsar magnetosphere are accelerated in a termination shock wave and then emit synchrotron radiation in the magnetic field of

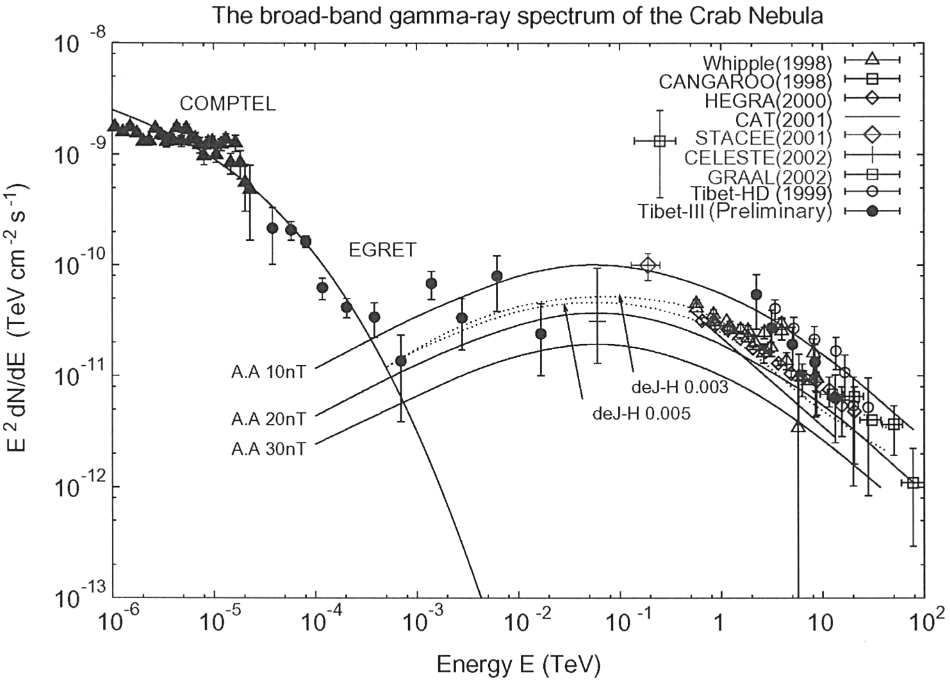

Figure 1. Broad-band energy spetcrum of unpulsed gamma rays from the Crab Nebula.

the nebula. Subsequently, TeV gamma rays are produced by inverse Compton scattering of the synchrotron-emitting electrons with various seed photon fields (synchrotron, dust emission, cosmic microwave background). There is now reasonable agreement between the TeV spectra of different groups, shown in Fig. 1 where the spectrum can be fit by a single power law.

Shell-type supernova remnants (SNRs) are widely believed to be the primary sources of cosmic rays upto $\sim 10^{15}$ eV. Various models of diffusive shock acceleration in different types of SNRs make predictions of the expected TeV gamma-ray fluxes. Experimentally, there are now three TeV sources of shell-type SNRs.

The first detection of TeV emission from a shell type SNR was SN1006 by the Cangaroo group (Tanimori 1998) at energies above 1.7 TeV. The ASCA X-ray image of SN1006 shows two bright rims of non-thermal emission implying the presence of electrons with energies up to 100 TeV. The TeV gamma-ray emission is localized along the NE rim, and can be modelled by energetic electrons producing inverse Compton radiation seeded by the cosmic microwave background (Mastichiadis & de Jager 1996). HEGRA successfully detected a very weak (33 milli-Crab equivalent) TeV gamma-ray flux from SNR CAS-A. The 2 results are explained (Drury et al. 1994; Brezhko & Aharonian 1997 ; Baring 1999) by electron acceleration, though they are not inconsistent with hadronic origin.

Very recently, the Cangroo group (Enomoto 2002)claimed evidence for TeV gamma rays of non-electron origin from SNR RXJ1713.7-3946, implying evidence for proton acceleration in SNR. This very interesting result invoked a sparm of discussions and need more study, i.e. confirmation by H.E.S.S., GLAST results, theoretical considerations, more multi-wavelength observations.

3.2. Extragalactic Gamma-ray Sources

Sofar, all the detected extragalactic TeV sources belong to the blazar class of active galactic nuclei (AGNs). It is believed that AGNs are composed of an accretion disc surrounding a central massive black hole and relativistic outflows perpendicular to the disc, which are called jets. In blazars, the jets are assumed to be closely aligned with the line of view. Models of TeV gamma-ray emission from blazar jets are classified into two categories depending on the assumed jet contents (hadronic models:p e^-, leptonic models: e^+ e^-). Hadronic models are attractive as they involve the acceleration of cosmic rays up to 10^{19} eV, whereas leptonic models naturally explain the present data. Out of eight TeV blazars observed sofar (Mrk421, Mrk501, 1ES2344+514, 1ES1959+650, PKS2155-304, 1ES1426+428, BL Lac, 3C66A), Mrk421, Mrk501, 1ES1426+428, 1ES1959+650 are confirmed sources. Here, we will concentrate on Mrk421 and Mrk501 which are confirmed by many experiments. The first outstanding feature of blazars is their flux variability. In 1997, Mrk501 underwent a giant flare lasting many months, with a mean source strength above 1 Crab and flares up to 10 Crab. Variability was seen on timescales down to hours. In Mrk421, short flares with doubling times of 15 to 30 minutes was detected (Gaidos 1996). This sets severe constraints on the size of the emission volume and implies bulk Lorentz factor of 5 to 10. Since 1995, multi-wavelength campaigns with instruments in other wavelength bands, in particular,with X-ray satellites, have been carried out to simultaneously observe TeV blazars. These show a good correlation between the TeV and X-ray fluxes. Analysis of simultaneous HEGRA and RXTE data of Mrk501 in 1997 shows the TeV flux rising quadratically with the X-ray flux (Krawczynski et al. 2000). This result can be interpreted in terms of leptonic synchrotron-self-Compton models. Simultaneous fit to the X-ray and TeV energy spectra gives values of the bulk Lorentz factor, the size of the emission region, and the magnetic field strength.

Very recently, Mrk421 was in a flaring state again in the years 2000 and 2001, and detected by many groups. The HEGRA (Aharonian et al., 2002) and Whipple (Kennrich et al. 2002) groups reported the spectral variability in the flares. The HEGRA group (Aharonian et al. 2002) observed a cut of energy in the energy spectrum at $3.6^{+0.4+0.9}_{-0.3-0.8}$ TeV and $6.2^{+0.4+2.9}_{-0.4-1.5}$ TeV, in Mrk421 and Mrk501 respectively, suggesting instrinsic difference in the gamma-ray emission mechanism between Mrk421 and Mrk501. Meanwhile, the Whipple group (Krennrich et al. 2001) reported a cut of energy in the energy spectrum at $4.3^{+0.3+1.7}_{-0.3-1.4}$ TeV and $4.6^{+0.8}_{-0.8}$ TeV in Mrk421 and Mrk501 respectively, suggesting absorption by interstellar photons. To solve this discrepancy, we need more data at diffrent redshifts.

4. Next-generation IACTs

Four next-generation IACT experiments, Cangaroo-III, H.E.S.S, MAGIC, and VERITAS, will get started in the years 2002 to 2005 with an order of magnitude improvement in sensitivity and an order of magnitude lower energy threshold (30 - 100 GeV). H.E.S.S. announced the first telescope out of four started its operation very recently (Gaisser 2002).

With these instruments, GeV-TeV astronomy has an exciting future ahead: high source statistics of known sources, searches for new sources believed to emit high energy radiation, precise spectroscopy, and mapping of TeV new sources expected to be discovered by next-generation satellite experiments (AGILE, GLAST, AMS-2). This will lead to better and deeper understanding of non-thermal pictures of the Universe.

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