Recent Topics from Very High Energy Gamma-ray Astrophysics

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Abstract

Recent results from very high energy gamma-ray astrophysics are presented. Topics are selected mainly from observations of TeV gamma-rays with atmospheric Cherenkov telescopes covering galactic and extragalactic sources.

1. Introduction

Thick atmosphere of the earth forces direct observations of gamma-rays on satellites in space, but at higher energies Cherenkov light (for $E_\gamma \gtrsim 50$ GeV) or particles (for $E_\gamma \gtrsim 10$ TeV) produced in particle showers caused by gamma-rays in the atmosphere reach ground level. Recently ground-based observation of gamma-rays has become a field of astronomy after succeeding in the reduction of overwhelming background of charged cosmic rays with improvement of detection techniques [1]. Here is reported some recent topics from the ground-based gamma-ray astrophysics, mainly based on observation of TeV gamma-rays with atmospheric Cherenkov telescopes.

Cherenkov photons emitted by particle showers in the atmosphere initiated by gamma-rays come to ground as a disk of about 300 m in diameter and a few meter in thickness. This size of Cherenkov light pool enables us to detect such light in large detection area of order 10^5 m^2. Atmospheric Cherenkov telescopes collect Cherenkov photons with large area reflectors and detect their short (several nanoseconds) light flash by fast photosensors. There is, however, a severe background: cosmic-rays, high-energy protons and nuclei bombarding the earth, produce Cherenkov light far more frequently in the earth atmosphere. Cosmic-ray showers are initiated by nuclear interaction of cosmic-ray protons or nuclei with atmospheric nuclei. The nuclear interaction produces mainly pions. Neutral pions decay promptly into two gamma-rays and develops electromagnetic showers. Charged pions interact atmospheric nuclei again and develop nuclear cascades. Transverse momenta of secondary pions produced in nuclear interactions are rather large and cosmic-ray showers are more diffuse than gamma-ray showers in general. The idea of an imaging Cherenkov telescope was proposed in late 1970's [2]. Later, Hillas [3] developed a method to discriminate gamma-ray showers from cosmic-ray showers using this difference of Cherenkov light image quantatively: he defined characteristic parameters called *length, width, distance, concentration* and showed the difference in distrtibution of these image parameters can be used to select gamma-ray showers from overwhelming background cosmic-ray showers statistically, even though it is hard to distinguish gamma-ray showers from cosmic-ray showers event by event.

The Crab nebula was the first object detected at TeV energies with high significance by the Whipple group in 1989 using this imaging technique [4]. After this breakthrough, many groups detected this source repeatedly and the Crab is now called as a "stantard candle" of the ground-based gamma-ray astronomy as well as in X-ray astronomy.

Then, image orientation angle toward the assumed source, or α, has been introduced as another effective image parameter [5, 6]. A gamma-ray signal appears as an excess events near $\alpha = 0°$ of its distribution and this is now the standard parameter used in analysis of data acquired with single Cherenkov telescope. The first demonstration of this method was the discovery of the first extragalactic TeV gamma-ray object, Mrk 421, in 1992 [7].

In this report recent topics in this field are summarized. More detailed and wider descriptions can be found in elsewhere [8].

2. Galactic objects

Supernova remnants are assumed to be the origin of galactic cosmic rays for long time. From energetics argument they can supply enough power to the total power of cosmic rays. However, the maximum energy accelerated in the expanding blast waves in supernova remnants is around 10^{14} eV and this fact has been dissuade many times in relation to the existence of "knee", the break in the all-particle cosmic ray energy spectrum around 10^{15} eV. We know there are more than 200 supernova remnants in our galaxy but we do not know how much of them could be the source of cosmic rays.

The first established TeV gamma-ray source, the Crab nebula [4], is known to be powered by the spin-down energy of a central fast-spinning pulsar. TeV emission is unpulsed and is believed to come from the pulsar wind nebula (so-called plerion system) via synchrotron-self-Compton mechanism in which synchrotron photons are scattered up to high energies by accelerated electrons. There are other TeV sources similar to this category: PSR1706-44 [9] and Vela [10], but their emission mechanism seems to be different from that of the Crab nebula and is not fully understood.

Recent reports on detection of TeV gamma-rays from supernova remnants showing non-thermal X-ray emission, SN1006 [11] and RX J1713.7-3946 [12], support the supernova origin of cosmic rays, but the TeV emission could be ascribed to high-energy electrons which up-scatters ambient photons to gamma-rays via inverse Compton emission [13]. Thus the evidence of proton acceleration, which is the proof of the supernova remnant origin of cosmic rays, is not strong, although there is an indication of proton acceleration in the TeV data measured by the CANGAROO group [14], of which interpretation may not be mandatory [15, 16]. The HEGRA group reported a detection of another supernova remnant, Cas A, based on long observation of 232 hours with their stereoscopic telescope system [17], which might be ascribed to proton acceleration, but its weak flux does not allow detailed spectral study to draw conclusion.

New observations of SN1006 have been reported at the last International Cosmic Ray Conference (ICRC) in 2003. The HEGRA CT1 group reported a 5σ excess of events toward the CANGAROO "hot spot" based on 219-hr observation at large zenith angles which corresponds to $E_\gamma > 18$ TeV [18]. Meanwhile, the observation by the first two telescopes of H.E.S.S. did not reveal a gamma-ray signal although their observation is less than 10 hours [19].

The HEGRA CT system reorted a detection of an unidentified source near Cygnus OB2 association [20] and it has been confirmed by new observations [21]. This source, called as TeV J2032+4130, shows a hard spectrum ($dN/dE \propto E^{-1.9}$) but there found no counterpart object in X-rays or optical wavelengths. It might be related to Cyg X-3, which was claimed to be a strong 10^{15} eV gamma-ray source in 1980's but the unidentified source position is well apart from the putative source.

The CANGAROO group reported observations of two supernova remnants from which non-thermal X-ray emissions were observed at ICRC 2003. SNR RCW86 showed tantalizing 4σ excess [22] and SNR RX J0852.0-4622 was detected above 5σ significance [23]. Also this group observed the Galactic center for two successive years and obtained a preliminary signal at more than 5σ level [24]. The emission mechanism of the Galactic center is an interesting issue and will be of great importance if the emission is confirmed by other groups.

A wide-area survey of the galactic plane has been executed by the HEGRA CT system, covering more than 3% of the entire sky and a few candidate gamma-ray sources were reported [25].

3. Extragalactic sources

Active galactic nuclei are the most common objects identified in the GeV gamma-ray sky and most of them are classified as blazars [26]. The second established TeV gamma-ray object following the Crab was Mrk 421 which is a nearby ($z = 0.031$) blazar [7]. Blazars show nonthermal emission spectra and there can be seen two peaks in general which is interpreted as synchrotron peaks caused by accelerated electrons in magnetic fields and inverse Compton peaks where synchrotron (or external) photons are up-scattered by high energy electrons. While hadronic models, where proton-initiated cascades produce high-energy emissions, are still viable, the synchrotron-self-Compton (SSC) model is a popular one on its simpleness. In addition to Mrk 421, large gamma-ray flares were detected on other nearby blazars, Mrk 501 (observed by many groups in 1997) and H 1426+428 (observed in 2001). Thus the number of blazars detected at TeV energies are increasing and providing good samples to test these emission models.

Detailed study of Mrk 421 were reported by various groups at ICRC 2003. STACEE, a large-area non-imaging Cherenkov detector utilizing solar power array, detected this source at median energy of 140 GeV [27]. CELESTE, another detector utilizing a solar power array, studied its spectrum in the 70-400 GeV region which is compatible with contemporary results from the CAT telescope [28]. Those strong flares were detected by some surface air shower detectors. Milagro, a water Cherenkov detector, detected Mrk 421 at 4.4σ level in their 2.4 yr data [29]. Tibet array, a high-altitude air shower array, observed Mrk 421 at 5.5σ significance around 3 TeV in 2 years [30]. At sub-TeV energies, the Whipple group observed its flaring activity in Dec. 2002-Jan. 2003 period [31]. Study of hourly variability showed the spectral variations were observed for one burst but no variations seen for another, which may not be accounted for using a simple one-component model [32].

Activities of H 1426+428 (blazar, $z = 0.129$) at TeV energies between 1999 and 2002 were studied by Whipple [33] and the HEGRA CT system [34] and the long-range light curve was obtained, showing correlation with X-ray activities.

1ES 1959+650 (blazar, $z = 0.048$) was once reported as a TeV gamma-ray emitter by the Utah 7TA group [35] with marginal significance of 3.9σ. In 2002 large flares occurred and were observed by the HEGRA CT system [36], HEGRA CT1 [37], and Whipple [38]. Now this source became an established source of TeV gamma-rays.

1ES 2344+514 (blazar, $z = 0.044$) was once reported as a TeV gamma-ray emitter by the Whipple group [39]. Observation by the HEGRA CT system confirmed TeV gamma-ray emission at 4.4σ level [40].

PKS 2155-304 (blazar, $z = 0.116$) was detected by Durham Mark6 telescope before [41]. The CANGAROO group reported upper limit in their 2000-2001 observations [42]. In 2002 H.E.S.S. detected this blazar repeatedly at high significance level (11.9σ in total) in July and October [43] and this source has been confirmed as a TeV emitter.

TeV gamma-rays are lost by pair creation process with EBL (Extragalactic Background Radiation) photons in the infrared region [44] and the spectra at these energies contain information on this EBL whose direct detection is difficult and often measurements are controversial.

Spectra of Mrk 421 and Mrk 501 was compared with the homogeneous SSC model taking account of EBL absorption and consistent results are obtained [45]. The EBL model dependence was also studied for H 1426+428 by the HEGRA group [34]. There is an evidence of spectral hardening above 1 TeV but the intrinsic spectrum after correction of EBL absorption depends on the EBL models, reflecting the uncertainty in the infrared measurements. Similar studies for Mrk 421 and Mrk 501 using the Whipple data were also reported [46].

The CANGAROO group reported a detection of a starburst galaxy, NGC 253, at TeV energies [47] which may constitute a new class of high-energy gamma-ray objects. Other starburst galaxies, M82, M81, IC 342, and NGC 3079, were observed by the Whipple group, but there were no positive signals [48]. Nearby galaxies, Dra/UMi dwarf, M33 were looked by the Whipple group to search for signals from dark matter neutralino annihilation [49].

Radio galaxies were long-sought TeV gamma-ray candidates for more than 40 years ago [50]. One of radio galaxies, M87, or Vir A ($z = 0.00436$ or 16 Mpc), was detected by the HEGRA CT system based on 83.4-hr observations [51]. While upper limits were given by the Whipple group [52], these are not inconsistent with the HEGRA detection. Thus this is a new type of TeV gamma-ray objects. While the emission from M87 with its parsec scale jet could be accounted for by the SSC model [53, 54], theoretical studies were presented to explain this emission utilizing proton blazar model and supposing emission from torus around the central supermassive black hole which could produce highest-energy cosmic rays [55].

4. New projects

The "Big Four" Cherenkov telescopes, which are sometimes called the "third generation" following the second generation (imaging) telescopes, are being completed or under construnction. CANGAROO-III (completed in 2003) is an array of four 10m telescopes in South Australia [56]. H.E.S.S. (to be completed in

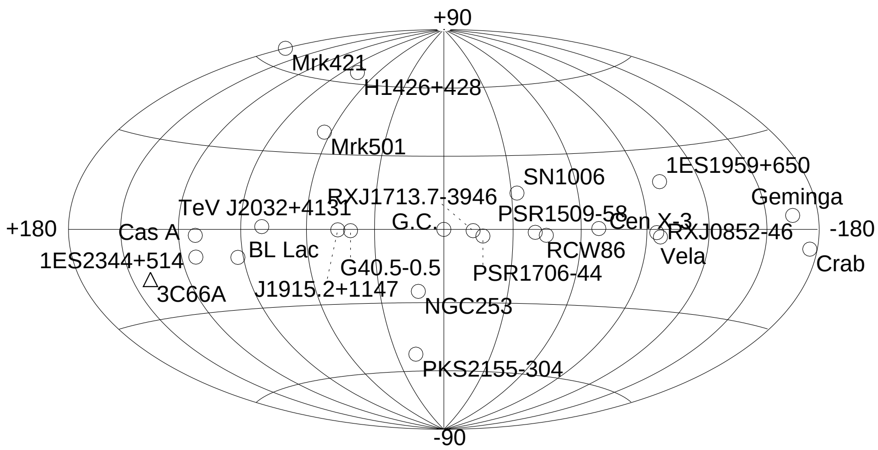

Fig. 1. Skymap of TeV gamma-ray sources as of 2003.

2004) is an array of for 12m telescopes in Namibia [57]. MAGIC (to be completed in 2003) is a 17m telescope in Canary Island [58]. VERITAS (to be completed in 2006) is an array of seven (initially four) 12m telescopes in Arizona [59]. These new Cherenkov telescopes will achieve unprecedented sensitivities to gamma-rays in the 100 GeV energy region, which nearly overlaps the energy region covered by the next-generation satellite gamma-ray observatory, GLAST, to be launched in 2006 [60].

5. Summary

TeV gamma-ray astrophysics using imaging atmospheric Cherenkov telescopes is becoming an indispensable field of astronomy. Very high energy sources may contain large varieties of active astrophysical objects, including both galactic and extragalactic objects. Figure 1. shows the latest skymap of TeV gamma-ray sources and Figure 2. shows the number increase of point sources as a function of time at high energies. The "third generation" Cherenkov telescopes are about to increase gamma-ray sensitivities to the unprecedented level from which we hope to obtain detailed information and to find new discoveries.

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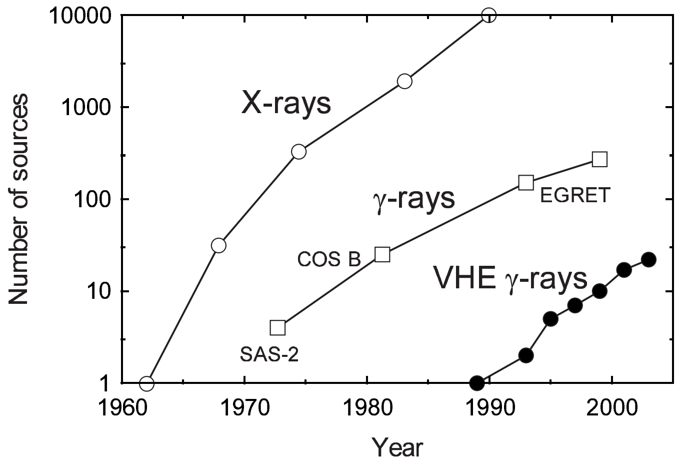

Fig. 2. Number of detected point sources versus time.

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