A Powerful Tool for Very-High-Energy Gamma-Ray Astronomy: Imaging Atmospheric Cherenkov Telescope Postprint

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Abstract

The achievements in ground-based very high energy (VHE) gamma-ray astronomy are largely inseparable from the development of imaging atmospheric Cherenkov telescope technology. The concept of atmospheric Cherenkov technology was proposed in the 1950s, achieved significant breakthroughs in the late 1980s and early 1990s, and gradually matured in the early 21st century. Stereoscopic imaging atmospheric Cherenkov telescope arrays have become a key detection technology for ground-based VHE gamma-ray astronomy due to their excellent angular resolution, energy resolution, and superior gamma/proton discrimination capability, and are widely employed in existing and planned ground-based gamma-ray detection facilities. This paper provides an overview of the history and current status of imaging atmospheric Cherenkov technology development, including the current status of ground-based VHE gamma-ray detection, the detection principle of atmospheric Cherenkov telescopes, technological evolution, representative current imaging atmospheric Cherenkov telescope arrays, and future development prospects.

Full Text

Preamble

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Imaging Atmospheric Cherenkov Telescope: A Key Instrument in VHE γ-ray Astronomy Observation

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Abstract

Ground-based very high energy (VHE) γ-ray astronomy achievements are inextricably linked to the development of imaging atmospheric Cherenkov telescope technology. The atmospheric Cherenkov technique was first conceived in the 1950s, achieved major breakthroughs in the late 1980s and early 1990s, and gradually matured in the early 21st century. Stereoscopic imaging atmospheric Cherenkov telescope arrays, with their excellent angular resolution, energy resolution, and superior γ/p discrimination capability, have become the key detection technology for ground-based VHE γ-ray astronomical observations and are widely employed in existing and planned ground-based γ-ray detection facilities. This paper provides an overview of the history and current status of imaging atmospheric Cherenkov technology development, including the status of ground-based VHE γ-ray detection, the detection principle of atmospheric Cherenkov telescopes, technological evolution, current typical imaging atmospheric Cherenkov telescope arrays, and future developments.

Keywords: very high energy γ-ray astronomy; imaging atmospheric Cherenkov technique; γ/p discrimination; stereoscopic observation

1 Introduction

VHE γ-rays (30 GeV–30 TeV) and above from celestial sources are believed to be produced almost exclusively through interactions of relativistic particles with surrounding matter or photon fields. Through measurements of VHE γ-ray photons, we can obtain information about the origin, acceleration, and propagation of high-energy particles in the universe, as well as the extreme environments where these processes occur [1-4], such as the origins of galactic and extragalactic cosmic rays, particle acceleration and propagation processes in extreme environments, and non-thermal transient phenomena like gamma-ray bursts (GRBs). Additionally, these VHE γ-rays provide a unique tool for multi-wavelength and multi-messenger astrophysics research. For example, extragalactic background light (EBL) and intergalactic magnetic field information can be obtained through measurements of γ-rays from extragalactic sources, and characteristic γ-rays from potential dark matter particles may also lie in the VHE band [5].

Due to severe absorption of high-energy photons by Earth’ s atmosphere, the most ideal method for detecting cosmic γ-rays is to place detectors in space for direct measurement. However, space detectors have very limited effective area due to payload constraints, while cosmic γ-ray flux decreases sharply with energy following a power-law spectrum, resulting in extremely low photon fluxes at higher energies. Therefore, studying VHE and higher-energy cosmic γ-rays requires a detector with enormous effective area, far exceeding the practical size of current space-borne instruments (approximately 1 m^2). Atmospheric Cherenkov telescopes perform indirect measurements by detecting Cherenkov light produced by atmospheric particle cascades (extensive air showers, EAS) initiated by cosmic γ-rays, using Earth' s atmosphere as the detection medium, enabling target collection areas to easily exceed 10^5 m^2.

The application of atmospheric Cherenkov telescope technology in γ-ray astronomy began with the explorations of Jelley and Galbraith in the 1950s. Early detections were unsuccessful due to interference from numerous cosmic ray charged particles. It was not until 1989 that the Whipple telescope first discovered VHE γ-ray radiation from the Crab Nebula, a breakthrough that benefited from the Whipple telescope' s development of an effective method to record Cherenkov radiation images of air showers, where imaging characteristics could be used to discriminate between γ-rays and cosmic ray charged particles (background), i.e., γ/p discrimination. In the late 1990s, breakthroughs in stereoscopic imaging technology and expanded telescope apertures greatly improved the sensitivity of atmospheric Cherenkov telescopes. Since then, Imaging Atmospheric Cherenkov Telescope (IACT) arrays have entered a period of rapid development, with renowned telescopes such as H.E.S.S. (High Energy Stereoscopic System), MAGIC (Major Atmospheric Gamma-ray Imaging Cherenkov Telescopes), and VERITAS (Very Energetic Radiation Imaging Telescope Array System) being successively constructed and achieving a series of important results in VHE γ-ray observations.

This paper takes the development and evolution of imaging atmospheric Cherenkov telescopes as its main thread, introducing the current status and principles of VHE γ-ray detection, and providing a brief review and summary of the development, evolution, and key technological breakthroughs of two generations of imaging atmospheric Cherenkov telescope technology. On this basis, we introduce current mainstream IACT arrays and their major achievements, compare the advantages and disadvantages of different ground-based γ-ray detection facilities, and provide an outlook on the development of next-generation ground-based VHE γ-ray detection technology.

2 VHE γ-ray Astronomical Observation

Before the emergence of cosmic γ-ray detectors in the 1940s–1950s, astronomers had predicted that certain astrophysical processes could produce γ-ray radiation, such as interactions between cosmic rays and interstellar matter, interactions between accelerated electrons and magnetic fields, and supernova explosions [6, 7]. In 1968, Clark et al. [8] first observed cosmic γ-rays using the OSO-3 satellite, opening a new window for human understanding of the universe. In 1972, the SAS-2 satellite experiment ($E > 35$ MeV) [9] first provided statistically significant γ-ray radiation measurements, discovering the Crab Nebula and Vela Nebula along with pulsar periodic signals, marking the true beginning of γ-ray astronomy research. In the late 1980s, the imaging Cherenkov telescope

Whipple first observed significant excess from the Crab Nebula above 0.7 TeV, ushering γ-ray astronomy into the TeV era [10]. In addition to further developing Cherenkov telescopes and satellite experiments, scientists also experimented with other new technologies, such as non-imaging Cherenkov telescopes [11, 12], heliostats [13], and extensive air shower secondary particle detection techniques. Non-imaging Cherenkov telescopes and heliostat technologies could not compete with second-generation IACTs in key parameters such as sensitivity, γ/p discrimination, energy resolution, and angular resolution, and were gradually phased out. EAS arrays based on high-altitude secondary particle detection technology (traditional EAS arrays such as ASγ and ARGO-YBJ, water Cherenkov detectors such as Milagro and HAWC) have achieved considerable development in ground-based VHE γ-ray astronomical observations since the early 21st century, after breaking through the key technology of γ/p discrimination, due to their advantages of large field of view and all-weather observation, becoming another successful observation technique alongside IACT and satellite experiments. The evolution of γ-ray astronomical observation technology is shown in Figure 1 [Figure 1: see original paper] (as of 2010; subsequent developments in ground-based detection technology are described in more detail in Sections 2.2, 6.1, and 6.2). Generally, γ-rays with $E < 1$ TeV can be detected directly, while those with $E > 1$ TeV can only be observed indirectly.

Note: Light blue on the left represents space detection, green in the middle represents IACT detection, and the right side represents air shower particle detection; in IACT technology, green indicates single telescopes, red indicates stereoscopic observation.

2.1 Direct Observation

Direct observation typically employs high-altitude balloons or satellites to directly measure γ-rays. Detectors include conversion layers, tracking chambers, calorimeters, and anti-coincidence detectors, with a typical example shown in Figure 2 [Figure 2: see original paper] (Fermi-LAT detector). When γ-rays reach the detector, they interact with matter in the conversion layer to produce electron-positron pairs; the tracking chamber measures the trajectories of these pairs, while the calorimeter measures their deposited energy. Based on this information, the incident direction and energy of γ-rays can be reconstructed. The anti-coincidence detector, typically composed of scintillators, is used to exclude charged particle events. Space detectors can precisely distinguish γ-ray events from cosmic rays and reconstruct their direction and energy.

From 1975 to 1982, the COSB-2 satellite [15] observed 25 cosmic γ-ray point sources above 100 MeV. In 1991, the CGRO satellite [16] was launched, carrying detectors including the Burst and Transient Source Experiment (BATSE), Oriented Scintillation Spectrometer Experiment (OSSE), Imaging Compton Telescope (COMPTEL), and Energetic Gamma Ray Experiment Telescope (EGRET), covering an energy range of 10 keV–30 MeV. During 1991–2000, CGRO/EGRET (20 MeV–30 GeV) detected nearly 300 γ-ray sources, some of which were identified, while CGRO/BATSE detected over 2,700 GRBs and proved that GRBs originate from extragalactic galaxies [17, 18]. In 2008, the Fermi telescope was launched, carrying the GBM and LAT detectors: the GBM detector operates mainly in the low-energy region (8 keV–40 MeV) with a field of view of 9.5 sr, covering almost the entire sky (except toward Earth); the LAT detector operates mainly in the high-energy region (20 MeV–300 GeV) with a field of view of 2.4 sr, effective area of about 1 m^2, energy resolution better than 10%, and angular resolution better than 3.5° at 100 MeV and better than 0.15° above 10 GeV [19]. As of 2018, Fermi has detected over 5,000 γ-ray sources in the 100 MeV–300 GeV energy range and over 2,300 GRBs [20, 21], ushering the GeV band into the true "thousand-source era." Source types include galactic sources such as supernova remnants (SNRs), pulsars and pulsar wind nebulae (PWN), binary systems, etc.; and extragalactic sources such as active galactic nuclei (AGN), normal galaxies, globular clusters, and starburst galaxies.

2.2 Indirect Observation

Indirect observation measures secondary particles produced by γ-rays interacting with atmospheric nuclei or Cherenkov light produced by these secondary particles to reconstruct γ-ray direction and energy information. Current mainstream technologies include imaging Cherenkov telescope (IACT) arrays based on secondary particle Cherenkov light detection and high-altitude secondary particle detection EAS arrays (indirect observation principles are shown in Figure 3 [Figure 3: see original paper]).

IACT focuses Cherenkov light produced by cosmic ray EAS secondary particles in the atmosphere onto photomultiplier tube (PMT) arrays via large-aperture mirrors for cosmic ray imaging detection, with typical representatives including MAGIC [22], H.E.S.S. [23], and VERITAS [24]. Current mainstream IACT arrays employ several telescopes to comprehensively measure Cherenkov light produced by cosmic ray showers, enabling excellent discrimination between γ-rays and cosmic ray backgrounds and precise reconstruction of the direction and energy information of primary cosmic γ-rays. Major achievements of second-generation IACTs will be introduced in Section 5.5.

Traditional EAS secondary particle detection arrays primarily measure EAS secondary particle arrival times and density distributions to reconstruct event direction, energy, and composition, thereby measuring cosmic ray energy spectra and anisotropy. Using differences in lateral distributions of EAS secondary particles, primary γ-rays and charged particle backgrounds can be distinguished to some extent, enabling detection of bright γ-ray sources, particularly transient sources. The Sino-Italian ARGO-YBJ array [25] employs this principle. Utilizing the significant difference in muon production between γ showers and hadronic showers at the same energy, constructing a surface array plus underground muon detector composite array can also effectively improve γ/p discrimination capability of EAS arrays, as employed by the Sino-Japanese ASγ+MD array [26, 27] and the under-construction LHAASO-KM2A array [28, 29]. The ASγ array and ARGO-YBJ array played important roles in monitoring high-state outbursts [30-33] and diffuse measurements [34, 35] of blazars Mkn421 and Mkn501. In 2019, the ASγ+MD array first observed γ-rays above 100 TeV from the direction of the Crab Nebula, advancing ground-based γ-ray detection to the sub-PeV energy region and opening a brand-new window [36, 37].

Water Cherenkov detector arrays [38] also belong to EAS arrays, but their detection principle differs somewhat from traditional EAS arrays, primarily detecting Cherenkov light produced by EAS secondary particles in water. Attempts to apply this technology to γ-ray astronomy and neutrino astronomy began in the 1990s, pioneered by the Milagro group (prototype Milagrito [39]). Although Milagro only detected a few TeV γ-ray sources [40, 41], it successfully lowered the γ-ray detection threshold to about 1 TeV and validated the effectiveness of water Cherenkov technology in VHE γ-ray astronomical observations. To further improve discovery capability, Milagro was upgraded to HAWC [42], with sensitivity improved by 15 times. HAWC has currently detected 65 TeV γ-ray sources, 26 of which are newly discovered, with the highest photon energy exceeding 100 TeV [43, 44].

The LHAASO-WCDA array also employs similar principles. Figure 4 [Figure 4: see original paper] compares the sensitivity of different ground-based detectors to cosmic γ-ray point sources, where LHAASO and CTA are under construction, while other experimental facilities have been completed. Detection sensitivity is defined as the minimum γ-ray flux above a specific threshold that can be detected (observing at least 10 events in 50 hours with significance exceeding 5σ). As shown in Figure 4, imaging atmospheric Cherenkov telescope arrays have lower detection thresholds, with minimum thresholds approaching 20 GeV, partially overlapping with satellite experiment energy ranges. In the 50 GeV–20 TeV energy region, it is difficult for other existing detection devices to compete with second-generation imaging atmospheric Cherenkov telescopes in terms of sensitivity. However, in the ultra-high energy region above 20 TeV, upgraded high-altitude secondary particle detection devices such as ASγ+MD, HAWC, and under-construction LHAASO have greater advantages. In terms of discrimination capability, HAWC' s discrimination ability has already reached equivalence with IACT arrays like H.E.S.S., and partially operational LHAASO' s discrimination capability has surpassed IACT, with sensitivity above 100 TeV far exceeding all previous experiments [29]. Additionally, imaging atmospheric Cherenkov telescope arrays have limited field of view (about 4°), making it difficult to observe bursting sources, transient sources, and extended sources, while high-altitude secondary particle detection devices with large field of view and all-weather characteristics are more suitable for detecting these sources. Overall, IACT and EAS detection technologies each have their own advantages and complement each other.

3 Atmospheric Cherenkov Light

When primary cosmic rays enter Earth’ s atmosphere and interact with atmospheric nuclei, they produce air showers. When charged particles in the shower move faster than the speed of light in air (v > c/n_{air}, where n_{air} is the refractive index of air), Cherenkov radiation is produced. Each particle generates Cherenkov light at a fixed angle (_c) relative to its direction of motion, which can be expressed as:

cos _c = v n_{air}

At sea level, this fixed angle is approximately 1.3°.

Cherenkov photon yield is wavelength-dependent and satisfies the following formula:

d^{2}N/dλdx = 2z$^2\pi\alpha$ (1/λ^2) sin^2 _c dλ

where z is the charge number of the particle, $\alpha = \mathrm{e}^2/(4\pi\ _0\hbar\mathrm{c})$ is the fine-structure constant. Atmospheric Cherenkov radiation is dominated by blue-violet light, peaking at about 340 nm (the number of photons emitted per unit length is inversely proportional to the square of the wavelength, while shorter wavelength radiation is essentially unable to reach the ground due to atmospheric absorption), with durations of several nanoseconds.

There are significant differences between Cherenkov light production processes initiated by VHE γ-rays and cosmic ray charged particles in the atmosphere. When VHE γ-rays enter Earth’ s atmosphere and interact with atmospheric nuclei, they first convert into electron-positron pairs, followed by bremsstrahlung and pair production interactions that cause electromagnetic cascades [46]. During the electromagnetic cascade process, particles undergo multiple Coulomb scatterings, causing the shower to develop laterally. Due to focusing effects caused by the variation of Cherenkov radiation angle with atmospheric depth, the final γ-shower Cherenkov light forms a Cherenkov “light pool” with relatively uniform light distribution within the pool. Figure 5 [Figure 5: see original paper] shows the theoretical simulation of the lateral distribution of the Cherenkov “light pool” formed by primary γ-rays of 10–500 GeV at sea level, with a “light pool” radius of about 130 m.

Charged cosmic ray particles (relativistic protons and nuclei) also produce air showers in Earth’ s atmosphere, but the cascade development process is more complex. Hadronic interactions proceed through various channels, producing secondary nucleons and charged and neutral pions with large transverse momentum. Pions have short lifetimes and essentially cannot reach sea level; neutral pions quickly decay into γ-rays, while charged pions produce muons and neutrinos. The γ-ray secondary particles produced by neutral pions trigger electromagnetic cascade showers, while the longer-lived muons form the most penetrating component of air shower particles reaching the ground. The result is that air showers initiated by charged cosmic ray particles develop much less regularly than those initiated by γ-rays. The shower images for γ-rays and charged cosmic ray particles are shown in Figures 6a [Figure 6: see original paper] and 6b, respectively (both at 100 GeV).

The differences in air shower morphology between cosmic ray charged particles and γ-rays enable IACT arrays to effectively distinguish γ-rays from the vast isotropic background of cosmic ray charged particles through differences in Cherenkov light imaging.

4 Development of IACT Technology

4.1 Early Exploration

Atmospheric Cherenkov light detection began with Jelley' s [48] accidental discovery: cosmic ray EAS secondary charged particles reaching the ground could be easily detected through Cherenkov light pulses they produced in liquids. After learning of this discovery, Blackett [7] pointed out that relativistic cosmic ray EAS secondary particles would also produce Cherenkov light in the atmosphere, estimating the Cherenkov light flux from cosmic ray EAS secondary particles to be about 10^{-4} of the night sky light flux. Galbraith and Jelley [49] subsequently observed about 1 or 2 pulses per minute in atmospheric Cherenkov light experiments and found these pulses correlated with cosmic rays detected by cosmic ray EAS arrays. Galbraith and Jelley inferred that not only cosmic ray EAS secondary charged particles could produce Cherenkov light through air showers, but also secondary charged particles from sufficiently energetic cosmic γ-ray EAS could produce Cherenkov light through air showers. Since Cherenkov radiation angle in low-density air is very small, this Cherenkov light is mainly confined within about 1.5° of the original photon position, thus the direction of Cherenkov light radiation could be used to determine the primary cosmic γ-ray source. To search for γ-ray sources, Galbraith and Jelley [50, 51] manually adjusted their telescope system in 1954 to point at strong radio sources Cyg A, Cas A, and the Crab Nebula. Due to too short exposure time and the large aperture allowing excessive background light, no significant excess of Cherenkov radiation was observed. Although Galbraith and Jelley did not detect cosmic γ-ray sources, their detection concept attracted significant scientific attention.

In 1959, at the biennial International Cosmic Ray Conference in Moscow, Cocconi [52] proposed that relativistic proton collisions would produce large numbers of γ-rays from π^0 decay, that the Crab Nebula was a TeV γ-ray source, and suggested searching for high-energy γ-ray sources through prominent high-energy shower point sources in the isotropic background.

In 1960, Chudakov' s team [53, 54] first responded to Cocconi' s suggestion, building the first atmospheric Cherenkov telescope (ACT) array for γ-ray observation on the Crimean Peninsula in the former Soviet Union. The ACT array consisted of 12 telescopes with 1.5 m diameter arranged at certain intervals. During four years of observation from 1960 to 1964, ACT found no significant excess of Cherenkov light pulses near the Crab Nebula or several other radio sources [55, 56]. During the same period, Porter [57] also began studying how to use Cherenkov signal pulses (later also radio pulses) to detect air showers and developed a "γ-photon receiver" for observing Cherenkov light from γ-showers. This receiver was a simple 3-fold coincidence PMT telescope system [58] with three 1 m diameter telescopes with focal length f = 0.5 m installed equidistantly for drift scanning. The "γ-photon receiver" operated for several years in mountains near Dublin, also finding no obvious anomalous Cherenkov light pulses.

In 1966, Weekes joined the Smithsonian project with γ-balloon detection pioneers Fazio and Helmken, beginning development of a 10 m aperture atmospheric Cherenkov telescope at the Whipple Observatory in Arizona, USA. The telescope was completed in 1968 and began operation. The Whipple telescope had a diameter of 10 m (f/0.7), with light collection elements initially being 12 cm PMTs located at the telescope focus, receiving cosmic γ-ray radiation within a 0.1° zenith angle range. To improve observation efficiency, the Whipple telescope later installed 2 PMTs on the focal plane separated by 2.4°, driving the telescope to point at potential γ-ray sources (radio-bright quasars, galaxies, or supernova remnants), with one PMT recording Cherenkov light from the "source" (on-source) and the other recording Cherenkov light from the background (off-source), hoping to discover sources by comparing the difference in pulse count rates between on-source and off-source modes. In 1972, Whipple [59] found about a 3σ excess in on-source counts from the Crab Nebula after more than two years of observation, at an energy of about 0.7 TeV. Due to large systematic errors between on-source and off-source modes and interference from a very bright star within 1° of the Crab Nebula, the Whipple research group could not determine whether the count excess came from the Crab Nebula or nearby cosmic background radiation. To further reduce cosmic ray charged particle background radiation, the Whipple telescope added additional biased PMTs to suppress off-axis Cherenkov light with significant angles to the telescope optical axis, shielding large amounts of atmospheric Cherenkov light produced by muons [60]. In subsequent years, the Whipple team scientists dedicated themselves to comprehensive scans of the northern sky, hoping to identify celestial sources through sudden increases in count rates in certain regions, though no obvious celestial sources were found. However, the multi-pixel PMT array method represented a crucial step in the right direction.

While the Whipple telescope was conducting observations, another γ-ray observation team led by Stepanian began in 1970 at the Crimean Astrophysical Observatory, using 2 pairs of 1.5 m reflectors to conduct long-term observations of the potential intermittent VHE γ-ray source Cygnus X-3. In the 1980s, this team' s work, similar to the Whipple observation team' s development of Cherenkov imaging technology, simultaneously guided the development of Cherenkov imaging technology.

In 1977, Weekes and Turver [61] proposed that the Whipple telescope use a new detector that would form a digital camera system using a 37-PMT array on the focal plane to record rough images of each air shower. The main idea was to shield all shower images inconsistent with the set direction and other complex images to exclude cosmic ray backgrounds, and proposed that a 2-telescope array separated by 100 m would provide stereoscopic images of Cherenkov light with shower axes pointing to celestial radiation sources. In 1981, at a Royal Society meeting, Weekes and Turver [62] simplified their initial idea, proposing the concept of a "first-generation" imaging atmospheric Cherenkov telescope: using a single telescope with a multi-pixel imaging system to record shower images produced by primary γ-rays.

Porter, Fegan, and Weeks subsequently began upgrading the Whipple telescope, with imaging units consisting of 37 photomultiplier tubes tightly arranged in a grid (hexagonal shape), covering a central region of 3.5° on the focal plane with pixel resolution of 0.5°. Concurrently, relevant computer simulation work began, with Plyasheshnikov and Bignami [63] conducting computer simulations of cosmic γ-ray imaging, showing that γ-ray shower images had clear directionality and were more compact compared to cosmic ray background shower images. This compactness provided a simple criterion for identifying cosmic γ-showers: the two brightest pixels contain more than 75% of the total signal. Using this criterion, Whipple found a 3–5.6σ excess in on-source observations compared to off-source observations of the Crab Nebula [64], representing the first successful observation by an imaging Cherenkov telescope.

Shortly thereafter, Hillas, at Weekes' invitation, began detailed simulation work specifically for Whipple telescope parameters [65], mainly studying shower images produced by γ-photons, protons, and other nuclei at different energies, different first interaction heights, and different arrival directions. Simulation results showed that most γ-ray shower images were regular and aligned with the source direction, while hadronic shower images were irregular and deviated from the original hadron source direction. In practice, if the brightness of each pixel is known, the original image can be reconstructed by simplifying it into an ellipse through the position of the γ-shower image centroid and the second moment of the light intensity distribution, giving an image axis passing through the shower center. The original image length and width are the semi-major and semi-minor axes of the simplified ellipse. When Hillas simulated the Whipple telescope imaging, the selected parameters are shown in Figure 7 [Figure 7: see original paper], and the comparison of Hillas parameters for Cherenkov light images produced by primary protons (dashed lines) and γ-rays (solid lines) is shown in Figure 8 [Figure 8: see original paper]. As can be seen from Figure 8, there are significant differences in Hillas parameters between Cherenkov light images produced by primary protons and γ-rays. By selecting appropriate Hillas parameters, telescopes can retain most γ-rays while suppressing large amounts of cosmic ray background. For example, by adjusting the most sensitive parameter "azimuthal width" (Azwidth), 98% of hadronic events can be rejected while retaining 67% of γ-ray events. More simulation details can be found in reference [67].

In the 1980s, with the operation of neutrino experiments, physicists urgently needed to observe VHE and higher-energy γ-rays. In 1988, the Whipple telescope imaging system underwent a major upgrade, with pixel units increased to 109. After the upgrade, pixel resolution doubled to 0.25°, covering a sky region of 2.8°. With the increase in imaging units, Hillas' criteria for γ-ray identification were also improved accordingly. γ-ray event selection no longer focused solely on the azwidth parameter but first screened "γ-ray-like" event image shapes, such as length, width, and distance from celestial sources, and further judged using the angle "α" between the shower image axis direction and the celestial source direction. In addition, confirmation of γ-ray events was further assisted by computer simulations and shower events outside the Cherenkov light pool. With the new judgment method, shower events in off-source detection were nearly randomly distributed, while in on-source detection, shower events showed significant excess within a small "α" angle range, making detection results easier to judge and evaluate.

After the upgrade, the Whipple telescope' s observation targets focused on γ radiation sources discovered by COS-B (1975–1982) and extragalactic objects discovered by CGRO-EGRET (mainly blazars). Two famous γ radiation sources discovered by CGRO-EGRET, Mkn421 and Mkn501, and the "standard candle" Crab Nebula quickly became Whipple telescope observation targets, with other blazars observed in subsequent years. The biggest breakthrough came in 1989 when Whipple first observed VHE γ radiation from the Crab Nebula [10], opening the door to ground-based VHE γ-ray astronomy. The Whipple telescope with imaging capability is also known as the first-generation imaging atmospheric Cherenkov telescope.

In addition to the Whipple telescope, the Soviet Stepanian observation group at the Crimean Astrophysical Observatory also adopted a similar but more advanced development approach. In 1989, the group completed the quite complex GT-48 detector—a γ-ray telescope with 48 mirrors (1.2 m) [68]. These mirrors were divided into 4 groups, each with 12 parallel telescopes, 8 of which were equipped with 37-pixel imagers with pixel spacing of 0.4° using normal PMTs and conical light guides, while the other 4 telescopes used UV-sensitive photomultiplier tubes to suppress hadronic shower background. The entire telescope system was divided into 2 parts separated by 20 m, with signals from imaging units of different telescopes superimposed. The telescope' s γ-ray event selection used image length, width, and direction parameters (using Plyasheshnikov' s calculations) and UV content. The GT-48 had an energy threshold of 1 TeV and could theoretically detect the above Whipple sources and other VHE γ-ray sources. Unfortunately, due to excessive system complexity, difficulty in upgrading, and lack of funding after the dissolution of the Soviet Union, GT-48 ceased operation around 2002.

4.3 Stereoscopic Observation

Shortly after the first Cherenkov telescope was used to search for cosmic ray sources, scientists attempted to improve sensitivity through stereoscopic observation technology, i.e., simultaneously detecting atmospheric Cherenkov light with several telescopes at certain intervals. In 1963, Chudakov' s team first attempted to design a multi-telescope stereoscopic system ACT (ACT consisted of multiple telescopes but could not image). In 1975, Grindlay attempted a stereoscopic observation method with only 2 similar telescopes installed on a circular orbit system allowing separations up to 180 m, but failed to achieve celestial source observations.

The key reason for the failure of early stereoscopic observation attempts was the inability to achieve γ/p discrimination. After Whipple' s breakthrough using pixelated cameras, some members of the Whipple collaboration transformed an 11 m solar telescope in New Mexico into a 37-pixel Cherenkov telescope for true stereoscopic observation. Unfortunately, this stereoscopic system had worse sensitivity than the Whipple telescope alone, due to poor mirror quality of the new telescope and the 120 m separation, preventing γ-ray events from being simultaneously detected by both telescopes.

The first prototype system to successfully implement stereoscopic observation and significantly improve detection sensitivity was established by the HEGRA collaboration. This prototype demonstrated the great superiority of stereoscopic observation technology, improving sensitivity by more than 10 times compared to single telescopes of the same aperture. In the last decade of the 20th century, scientists also built other imaging and stereoscopic observation systems (see Table 1), but none reached the sensitivity of the HEGRA experiment.

4.4 HEGRA-CT (High Energy Gamma Ray Array-Cherenkov Telescopes)

The HEGRA experiment included an air shower array consisting of 250 scintillators and several muon detectors, covering an effective area of 180 m × 180 m at an altitude of 2,200 m on La Palma in the Canary Islands. The scintillator detectors covered an energy range of 40–100 TeV. In 1998, 5 telescopes were built within 100 m^2 around the HEGRA detectors, forming the HEGRA-CT array. The HEGRA-CT array was the first true stereoscopic imaging Cherenkov telescope system. Each telescope had a 271-pixel imaging system with mirrors composed of 30 small circular mirrors of 60 cm diameter, equivalent to a 3.3 m aperture telescope, much smaller than the Whipple telescope aperture.

The working principle of the HEGRA-CT array is shown in Figure 9 [Figure 9: see original paper]. The principle uses at least 2 imaging Cherenkov telescopes deployed at distances comparable to the Cherenkov light pool radius (about 130 m) to measure γ-ray shower Cherenkov light images from different directions. Compared with traditional single telescopes, stereoscopic observation has obvious advantages: (1) Stereoscopic technology improves angular resolution by observing atmospheric showers from different perspectives with 2 or more Cherenkov telescopes, suppressing front-back ambiguity of single telescopes and effectively improving γ/p discrimination; (2) Redundant shower information from stereoscopic observation can control and reduce systematic errors in energy spectrum determination, providing better shower energy measurement capability, and combined with better angular resolution, allows study of extended sources; (3) Simultaneous triggering of multiple telescopes effectively suppresses interference from local muons and cosmic ray backgrounds, effectively lowering detection thresholds.

The HEGRA-CT array [79] greatly demonstrated the stereoscopic imaging principle. With pixel resolution of 0.25°, the arrival direction positioning accuracy for γ-rays could reach 0.14°. Even without using image shape (Hillas parameters) to exclude hadronic showers, γ-ray point sources could be easily identified. The HEGRA-CT energy threshold was 500 GeV. By retaining images with small "scaled width" and other features, about 90% of hadronic background could be suppressed while retaining 50% of γ-rays. The HEGRA-CT array operated from 1998, discovering a batch of new γ-ray sources such as Cas A, M87, and J2032+4130. The project was closed in 2002 to deploy larger MAGIC telescopes at the same location.

MAGIC has similar telescope spacing to HEGRA-CT but with lower energy thresholds.

4.5 Second-Generation IACT

In 1992, during the biennial International Cosmic Ray Conference, a workshop titled "Major Developments in Imaging Atmospheric Cherenkov Detectors" was held. Participating scientists reached the following consensus [80]: (1) VHE γ-ray sources indeed exist; (2) Cherenkov telescopes are the most promising VHE γ-ray astronomical instruments to date; (3) New detectors need larger light collectors to effectively lower detection thresholds; (4) Good γ/p discrimination capability is key to successful detection technology. The highlight of this conference was discussion of Cherenkov detection principles, affirming the major role of computer technology and microelectronics development in better understanding air shower development processes and detector responses, clarifying ideas for next-generation imaging atmospheric Cherenkov telescope development. Due to cost issues, no consensus was reached on building large scientific facilities. However, in subsequent years, key technologies for large telescopes, such as γ/p discrimination technology, larger apertures, finer imaging units, and stronger data readout capabilities, were systematically researched, and related difficulties were gradually overcome. In the last years of the 20th century, scientists clarified plans to establish several "second-generation" imaging atmospheric Cherenkov telescopes with larger light collectors and more pixelated cameras than HEGRA. H.E.S.S. and MAGIC research members mainly came from the HEGRA collaboration, VERITAS research members mainly came from the Whipple team, and CANGAROO came from Japanese and Australian research teams. Main parameters of second-generation imaging atmospheric Cherenkov telescopes compared with HEGRA-CT are shown in Table 2 . Since energy resolution and angular resolution are related to γ-ray energy and source position in the telescope field of view, the energy and angular resolutions given in the table are the best values achievable by the telescopes. Typical real images of second-generation imaging atmospheric Cherenkov telescopes are shown in Figure 10 [Figure 10: see original paper].

5 Second-Generation Imaging Atmospheric Cherenkov Telescopes

5.1 MAGIC

Due to disagreements on technical approaches for second-generation imaging atmospheric Cherenkov telescopes, the HEGRA-CT group split, with Lorenz et al. beginning research on a completely new MAGIC telescope. The research team built the MAGIC telescope in 2004 at the original HEGRA site. The goal was to collect sufficient photons to lower the threshold energy from about 250 GeV to about 20 GeV, making its detection energy overlap with satellite detectors (but with much higher sensitivity to faint sources than MAGIC).

MAGIC' s initial goal was to achieve this through improved light detection performance of a single (non-stereoscopic) telescope: larger optical size of the mirror—17 m diameter, finer imaging units, higher light conversion efficiency, etc. At the same time, an active control system continuously adjusted the direction of 1 m mirror segments to counteract mechanical deformation and improve angular resolution. While other second-generation imaging atmospheric Cherenkov telescopes determined γ-ray directions through the intersection points of shower axes from different two-dimensional images, MAGIC-I determined celestial source positions through the azimuth angle from the image centroid to the source [83] (similar to Whipple' s method). This method contributed little to event excess, but with increased MAGIC image clarity, it could effectively determine celestial source positions. Although MAGIC-I had very high sensitivity, the research group soon realized that stereoscopic observation was more efficient. In 2009, they added a second telescope 85 m from MAGIC-I to form MAGIC-II. MAGIC-II has an angular resolution of 0.11° at 300 GeV and 0.08° at 1 TeV, an effective field of view of 3.5°, and a threshold energy of 25 GeV.

5.2 H.E.S.S.

The H.E.S.S. project, led by Hofmann and Volk, developed from the HEGRA and CAT experiments [84], equipped with more powerful telescopes and cameras to effectively expand the field of view, enabling imaging of Cherenkov light from atmospheric showers falling in larger areas around the array, more effectively scanning the sky, particularly extended sources and necessary surrounding “non-source” regions (large shell supernova remnants, massive star clusters, etc.).

H.E.S.S. telescopes began formal observations in 2003, initially using 4 telescopes of 12 m aperture (H.E.S.S.-I) with 960 PMT imaging units, angular resolution of 0.16°, field of view of 5°, and threshold energy of 300 GeV. In 2012, a 27 m aperture telescope was added at the center of the original H.E.S.S.-I array, i.e., H.E.S.S.-II. H.E.S.S.-II has angular resolution of 0.07°, field of view of 3.6°, and threshold energy of 30 GeV. To date, H.E.S.S. has detected over 100 celestial sources, more than half located at low galactic latitudes, many of which are pulsar wind nebulae. These observations also include binary systems, possibly containing a stellar black hole, and 4 extended sources corresponding to supernova remnant shells.

5.3 VERITAS

The VERITAS project developed from Whipple, with planning beginning before the H.E.S.S. proposal. The initial plan was to build a 7-telescope array at the original Whipple site with separations no more than 10 m, but ultimately an asymmetric 4-telescope array was built. The VERITAS experiment consists of 4 telescopes of 12 m aperture, with angular resolution of 0.15°, field of view of 4°, and threshold energy of 50 GeV. VERITAS borrowed MAGIC-I’ s “displacement method” for γ-ray shower image reconstruction, greatly improving stereoscopic reconstruction accuracy for source positions at large zenith angles. VERITAS has been in full operation since 2007 and has discovered 24 new sources to date.

5.4 CANGAROO (Collaboration of Australia and Nippon for a Gamma Ray Observatory in the Outback)

The CANGAROO project initially used a single 3.8 m aperture imaging Cherenkov telescope with 256 PMT imaging units and angular resolution of about 0.1° [82]. CANGAROO-I began observations in 1992, discovering signal excess from some celestial sources including RX J1713.7-3946, Vela-X, and Vela Junior. In 1999, a 7 m aperture imaging Cherenkov telescope was built next to the 3.8 m telescope with 512 PMT imaging units and angular resolution of about 0.15° (CANGAROO-II). Subsequently, a plan to build 4 telescopes of 10 m aperture was put on the agenda (CANGAROO-III). As a first step, CANGAROO-II was upgraded to 10 m aperture in 2002, with pixel units upgraded to 552 PMTs and angular resolution of about 0.2°. The subsequent 3 telescopes had PMTs upgraded from 1/2 inch to 3/4 inch, with pixel units reduced to 427 PMTs, completed in 2004.

Unfortunately, CANGAROO-I’ s early immature image analysis procedures led to erroneous measurements of SN1006 [85]. After the stereoscopic array CANGAROO-III was built, the first of its 4 telescopes did not perfectly match the others and had to be excluded from the array, making it uncompetitive with H.E.S.S. Additionally, due to accidental damage to plastic crystals and other reasons, the CANGAROO project was terminated in 2011.

5.5 Major Observational Achievements of Second-Generation IACT

The success of ground-based VHE γ-ray astronomy lies not only in expanding the number of VHE γ-ray sources above TeV from 1 in 1989 to over 200 in 2020 but also in extending the types of TeV γ-ray sources and promoting the development of particle astrophysics and fundamental physics. This success mainly comes from the extensive sky surveys and discoveries by second-generation imaging atmospheric Cherenkov telescopes H.E.S.S., MAGIC, and VERITAS. Currently, 228 VHE γ-ray sources above TeV have been discovered, of which 183 were discovered by second-generation imaging atmospheric Cherenkov telescopes: H.E.S.S. discovered 111 VHE γ-ray sources above TeV, including 53 identified galactic sources (24 PWNe, 20 SNRs, 9 binary systems), 29 identified extragalactic sources (26 AGN-related, 1 dark matter-related, 5 other types), and 26 unidentified sources. MAGIC discovered 45 VHE γ-ray sources above TeV, including 6 identified galactic sources (2 PWNe, 1 SNR, 3 binary systems), 34 identified extragalactic sources (33 AGN-related, 1 GRB), and 5 unidentified sources. VERITAS discovered 24 VHE γ-ray sources above TeV, including 5 identified galactic sources (2 PWNe, 2 SNRs, 1 binary system), 15 identified extragalactic sources (13 AGN-related, 2 other types), and 4 unidentified sources. Basic information on VHE γ-ray sources above TeV is shown in Table 3 , and representative achievements of second-generation IACT are shown in Figure 11 [Figure 11: see original paper].

5.5.1 Pulsars and Pulsar Wind Nebulae (PWN) Pulsars are highly magnetized, rapidly rotating neutron stars whose outflows interact with surrounding media to produce a shock region where particles are accelerated, known as pulsar wind nebulae. To date, TeV VHE γ-ray radiation has been detected from only 2 pulsars (the Crab Nebula pulsar and Vela pulsar), while 36 TeV VHE γ-ray radiations have been detected from pulsar wind nebulae. H.E.S.S. has added a large number of such objects to the source catalog, among which the pulsar wind nebula N157B in the Large Magellanic Cloud is the only extragalactic stellar source and the most distant VHE γ-ray stellar source detected to date.

The Crab Nebula is the first celestial object where VHE γ-ray radiation from both the pulsar and pulsar wind nebula has been detected. In 2008, MAGIC discovered γ-ray radiation from the Crab Nebula pulsar at 26–100 GeV [87]. In 2011, VERITAS detected γ-ray radiation from the Crab Nebula pulsar at 100-400 GeV [88], with the radiation spectrum following power-law decay, results confirmed by MAGIC a few months later [89]. In 2014, MAGIC discovered bridge emission above 50 GeV from two pulsars [90]. In 2016, MAGIC found that the cutoff energy of Crab Nebula pulsar γ radiation extended to 1.5 TeV [91], posing a major challenge to existing theories.

5.5.2 Binary Systems About one-third of stars in the universe belong to binary systems, consisting of a massive star and a compact object orbiting a common center of mass. In the 1980s, astrophysicists generally believed that VHE radiation originated in binary systems. A certain number of VHE sources were subsequently discovered, but there was no evidence that these VHE γ sources were binary systems. In 2005, H.E.S.S. first announced the discovery of binary VHE γ sources PSR B1259-63 and LS 5039 in the southern sky [92, 93], subsequently discovering 5 more binary VHE γ-ray sources including J1018-589 A. In 2006, MAGIC announced the discovery of binary VHE γ-ray source LSI+61303 in the northern sky [94]. In 2017, VERITAS announced the discovery of binary VHE γ-ray source PSR J2032+4127 [95]. To date, IACTs have discovered 9 binary VHE celestial sources and 2 related VHE sources, while HAWC has discovered 2. Known VHE γ-ray radiation periods range from 4 days to 1,237 days. The measured γ-ray flux in binary systems varies with orbital phase. Except for the known pulsar in the PSRB1259-63 system, the compact object types, particle acceleration mechanisms, and γ-ray emission mechanisms in other binary systems remain unclear.

5.5.3 Supernova Remnants Supernova remnants (SNRs) are extended celestial objects formed by the interaction of supernova ejecta with interstellar medium, long considered the main source of galactic cosmic rays with maximum energies up to PeV. To date, 28 SNRs have been discovered as TeV VHE γ sources. The highest γ-ray energies currently observed are from Cassiopeia A (cutoff energy 3.5 TeV, MAGIC, 2017) [96] and RX J0852.0-4622 (cutoff energy 6.7 TeV, H.E.S.S., 2017) [97]. Notably, the recent ASγ+MD array discovery of SNR G106.3+2.7 as a potential PeV accelerator [98] is noteworthy.

5.5.4 Galactic PeV Accelerators Galactic cosmic rays can reach energies up to several PeV, implying the existence of PeV accelerators within the galaxy. Although previous observations inferred more than 10 "particle accelerators" in the Milky Way that could accelerate particles to tens of TeV, none of these sources showed accompanying γ-ray radiation that could accelerate particles to PeV (γ-ray power-law spectra extending to tens of TeV without cutoff). The H.E.S.S. collaboration analyzed the first 10 years of observations and found tens of TeV γ radiation near the supermassive black hole Sagittarius A* at the galactic center [99], which can be considered evidence for the existence of PeV particle accelerators, first proving that PeV accelerators may exist within the galaxy.

5.5.5 Active Galactic Nuclei (AGN) IACTs have detected 90 TeV VHE γ-ray sources in the VHE band. Except for 7 VHE γ-ray sources including the pulsar wind nebula N157B, starburst galaxies NGC253 and M82, globular cluster Terzan5, massive star clusters Westerlund1, Westerlund2, and J1848-018, all other extragalactic VHE γ-ray sources are related to AGN. Among these AGN VHE γ-ray sources, there are 8 flat spectrum radio quasars (FSRQs), 52 high-frequency peaked BL Lac objects (HBLs), 8 intermediate-frequency peaked BL Lac objects (IBLs), and 2 low-frequency peaked BL Lac objects (LBLs).

AGN are transient sources. Observations of AGN flare γ radiation can study supermassive black hole jets and their environments, particle acceleration, and VHE γ-ray emission mechanisms. Eight FSRQ flare events have been observed to date, with results from 2015-2017 [100-102]. MAGIC also observed γ-ray burst phenomena during the 2015 flare activity of PKS 1510-089 and simultaneously observed PKS 1510+089 γ-ray bursts in 2016, finding that VHE γ-ray flux changed dramatically while GeV band flux showed no obvious change [103]. Four BL-Lac flare events have been observed, with the most recent discoveries being S4 0954+65 (blazar, MAGIC, 2015), RGB J2056+496 (blazar, VERITAS, 2016), and TXS 0506+056 (blazar, MAGIC, 2017), plus the flare γ radiation from radio galaxy NGC 1275. Observations over several months in 2016-2017 showed large variations in nightly γ radiation flux, with the brightest γ radiation flux reaching 1.75 times that of the Crab Nebula γ radiation flux [104].

5.5.6 Gamma-Ray Bursts (GRBs) GRBs are one of the few astrophysical phenomena that can accelerate particles to extreme energies (10^{19} eV) and are excellent probes to unravel the mystery of ultra-high-energy cosmic rays (UHECRs). Previously, no ground-based observation device had detected GRB γ radiation above 100 GeV. In January 2019, MAGIC first observed γ-rays with E $>$ 300 GeV (GRB190114C) [105, 106], confirming Fermi-LAT observations from different energy bands and establishing the existence of self-Compton scattering components in GRB afterglows. H.E.S.S. subsequently observed γ radiation above 100 GeV deep in the afterglow of GRB180720B and VHE γ radiation from GRB190829A [107], posing major challenges to existing electron synchrotron radiation theories. These are also the first measurements by ground-based devices of GRB γ radiation above 100 GeV during the afterglow phase, opening a new energy window for multi-wavelength observations of GRBs. GRB190114C and GRB180720B were also observed by the Fermi-LAT satellite, providing multi-wavelength observations from a few keV to hundreds of GeV and offering more powerful observational means for further study of GRB central engines, radiation mechanisms, and new physical phenomena such as extragalactic background light constraints.

5.5.7 Extragalactic Background Light (EBL) EBL is the integrated light emitted by the entire universe. Understanding EBL properties is crucial for studying the intrinsic spectra of most blazars. MAGIC, H.E.S.S., and VERITAS have conducted EBL measurement work in recent years. H.E.S.S. and VERITAS use methods independent of spectral shape, while MAGIC uses several different EBL models for comparative measurements. Although methods differ, EBL-SED shape and intensity measurement results basically agree, with slight differences in different bands [108].

6 Future Development of IACT Technology

The success of second-generation imaging atmospheric Cherenkov telescopes has not only promoted the development of particle astrophysics and fundamental physics, gradually shifting scientists' research focus from "finding sources" to studying fundamental physics and basic physical problems, but also inspired scientists to upgrade and transform existing IACT telescopes, build or plan new ground-based VHE γ-ray telescopes, and continuously explore new detection technologies.

6.1 CTA (Cherenkov Telescope Array)

Significantly improving sensitivity is difficult to achieve by improving single telescope performance with existing technology, but can be realized by substantially increasing the number of telescopes in the array structure. The HEGRA prototype has already proven that stereoscopic observation technology has great superiority, with sensitivity greatly improved compared to single telescopes of the same aperture. Based on this consideration, CTA [109] aims to improve sensitivity by significantly increasing the number of telescopes in the array structure and cover a wider energy range by setting different aperture telescopes. CTA plans to improve existing IACT array sensitivity by 10 times, with observation energy spanning 4 orders of magnitude (20–300 TeV), intending to build an imaging atmospheric Cherenkov telescope array in both the southern and northern hemispheres (southern hemisphere site in Chile' s Atacama Desert, northern hemisphere site on Spain' s Canary Islands). The detection array consists of three types of telescopes: large-sized telescope (LST), medium-sized telescope (MST), and small-sized telescope (SST). Main parameters are shown in Table 4 . In addition to the traditional mirror-based MST prototype, CTA also designed a Schwarzschild-Couder telescope prototype (pSCT) with SiPM imaging units. For comparison, this telescope prototype' s parameters are also included in the table.

CTA mainly explores important scientific frontiers such as the origin of relativistic cosmic particles, extreme environments, and new physics. CTA' s larger field of view enables observation of extended sources, better angular resolution facilitates detailed source studies, better energy resolution enables fine measurements of energy spectra, faster slewing speed aids observation of bursting and transient sources, and lower detection thresholds enable effective connection with satellite observations.

6.2 Wide-Field Atmospheric Cherenkov Telescope Based on Lenses

Second-generation imaging atmospheric Cherenkov telescopes have much higher sensitivity than other existing detection devices in the 50 GeV–20 TeV energy region for γ-ray observations, but their limited field of view (about 4°) makes it difficult to observe bursting sources, transient sources, and extended sources. Scientists are actively exploring wide-field atmospheric Cherenkov telescope technology, proposing various solutions, among which an important direction is atmospheric Cherenkov telescope technology based on lenses [110]. The idea of using wide-angle lenses instead of traditional narrow-field mirrors to measure high-energy γ-rays was first proposed by David et al. in 1998 [111]. Subsequently, the GAW (Gamma Air Watch) plan [112] proposed using a wide-angle Fresnel lens of about 3 m diameter to observe VHE γ-rays. The JEM-EUSO (Extreme Universe Space Observatory) experiment plans to use 2 wide-angle Fresnel lenses of 1 m diameter to study ultra-high-energy cosmic rays [113]. Fresnel lens systems have advantages of large field of view and good transmittance but suffer from complex processing technology, high cost, and large off-axis imaging aberrations. Inspired by GAW and JEM-EUSO plans, Chinese researchers conducted preliminary research on wide-angle lens imaging technology, proposing the concept of a wide-angle atmospheric Cherenkov telescope based on water lenses (using a glass spherical shell + high-purity water to simulate human eye structure, fully utilizing high-purity water' s good transmittance for blue light and the good off-axis large-angle imaging consistency of hemispherical or thick lenses, with relatively simple technology). The main physics goal is ground-based detection of VHE γ transient sources (such as GRBs with ~100 GeV VHE γ radiation). A 0.9 m aperture spherical crown thin lens prototype was developed for principle verification. This prototype has jointly observed cosmic ray events with the Tibet Yangbajing small array YBJ-HA, verifying the lens system' s ability to detect atmospheric Cherenkov light and preliminarily confirming wide-angle performance [114-117].

6.3 Photoelectric Sensor Technology

The success of VHE γ-ray astronomy also benefits from continuous development of low-light detection technology, particularly the continuous improvement of PMT photoelectron detection efficiency. Currently, the best Cherenkov telescope imaging systems have average quantum efficiency of only 15%-18% in the typical spectral range of 300–650 nm. Further improving PMT quantum efficiency would undoubtedly enhance the discovery capability of existing telescope arrays. SiPM is essentially an array of avalanche photodiodes (APD) operating in Geiger mode, also known as multi-pixel photon counters (MPPC). Compared with traditional PMTs, SiPM has advantages of high quantum efficiency (80% for SiPM vs. 25%-40% for PMT), low operating voltage (2–80 V for SiPM vs. 1-3 kV for PMT), insensitivity to magnetic fields, small size, compact structure, and low mass production price. This technology was first explored and successfully implemented by FACT (First G-APD Cherenkov Telescope) [118, 119], and the MAGIC research team is also developing this technology [120]. Future LHAASO/WFCTA [121] and CTA/SST [122] cameras will also use SiPM.

7 Conclusion

In the 1950s, radio astronomy and later X-ray astronomy inspired the desire to “observe the universe through new windows,” leading to exploration of detecting primary cosmic γ-rays from the ground using Cherenkov light produced by relativistic secondary particles of extensive air showers in the atmosphere. Due to poor detector sensitivity and insufficient understanding of air shower development details, early Cherenkov light telescopes could not effectively distinguish cosmic ray charged particle components from γ photons. It was not until 1989, when the Whipple telescope first observed VHE γ radiation from the Crab Nebula, that effective observation of primary cosmic γ-rays was achieved. Imaging atmospheric Cherenkov telescopes have experienced three main stages: early exploration (non-imaging Cherenkov telescopes), imaging atmospheric Cherenkov telescopes, and stereoscopic imaging atmospheric Cherenkov telescopes, developing through two generations. Their maturation was based not only on expanded telescope apertures but mainly on two aspects: (1) development of highly effective γ/p discrimination technology that effectively eliminated the huge cosmic ray charged particle background; (2) development of stereoscopic imaging technology that greatly improved energy and angular resolution accuracy of primary γ-ray reconstruction and effectively lowered detection thresholds. After nearly 70 years of development, Cherenkov detection technology has achieved tremendous success. Stereoscopic imaging Cherenkov telescopes represented by H.E.S.S., MAGIC, and VERITAS have discovered over 100 new sources in the TeV VHE γ-ray energy range, including AGN, SNRs, globular clusters, binaries, etc., accounting for more than half of TeV VHE γ-ray celestial sources.

In addition to imaging Cherenkov telescope technology, traditional EAS arrays based on extensive air shower secondary particle detection, water Cherenkov detection, etc., have also achieved great success in VHE, particularly above 20 TeV, γ-ray observations, detecting ultra-high-energy γ-ray radiation above 100 TeV.

Compared with the number of X-ray sources and GeV γ-ray sources, the number of TeV VHE γ-ray sources is clearly too small. Current observational data cannot provide sufficient samples for scientists to deeply study VHE source radiation and their interaction mechanisms. Therefore, VHE and higher-energy γ-ray astronomical observation technology still needs vigorous development, including lower thresholds, larger fields of view, higher angular and energy resolution, and higher sensitivity. CTA improves sensitivity by significantly increasing the number of telescopes in the array structure and covers more energy ranges by setting different aperture telescopes. LHAASO improves sensitivity and broadens energy measurement range through composite arrays. Aharonian et al. [124] also suggested building large-aperture IACT arrays at higher altitudes (about 5,000 m) to lower thresholds and improve effective area, energy resolution, and angular resolution. In addition, more new technologies such as SiPM applications and computer development will also contribute to VHE γ detector performance improvements. With technological progress and construction and operation of new-generation observation devices, TeV VHE γ-ray sources will, like X-ray and GeV γ-ray sources, enter the "thousand-source era" in the near future, as shown in Figure 12 [Figure 12: see original paper], and VHE γ-ray observations will contribute "high-energy" power to the development of multi-wavelength and multi-messenger astronomy.

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