IMAGING ATMOSPHERIC ČERENKOV TELESCOPES:
TECHNIQUES AND RESULTS

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The hunt for cosmic TeV particle accelerators is prospering through Imaging Atmospheric Čerenkov Telescopes. We face challenges such as low light levels and MHz trigger rates, and the need to distinguish between particle air showers stemming from primary $\gamma$-rays and those due to the hadronic cosmic ray background. Our test beam is provided by the Crab Nebula, a steady accelerator of particles to energies beyond 20 TeV. Highly variable $\gamma$-ray emission, coincident with flares at longer wavelengths, is revealing the particle acceleration mechanisms at work in the relativistic jets of Active Galaxies. These 200 GeV to 20 TeV photons propagating over cosmological distances allow us to place a limit on the infra-red background linked to galaxy formation and, some speculate, to the decay of massive relic neutrinos. $\gamma$-rays produced in neutralino annihilation or the evaporation of primordial black holes may also be detectable. These phenomena and a zoo of astrophysical objects will be the targets of the next generation multi-national telescope facilities.

1 Introduction

$\gamma$-ray astronomy has traditionally been thought of as an extension of X-ray satellite experiments into the $\gamma$-ray regime. An all-sky survey by the most recent satellite experiment, EGRET (1991 - 2000), increased the catalogue of discrete astronomical sources of 20 MeV - 20 GeV $\gamma$-rays from 4 to 271. As a result, the question of what happens at energies beyond 20 GeV has gained momentum. Since the $\gamma$-ray count rate from these sources is a steeply falling function of photon energy, a sensitive area four orders of magnitude greater than EGRET's is needed for reasonable counting statistics in the Very High Energy (200 GeV - 50 TeV) $\gamma$-ray regime. To attain this we must make the absorbing atmosphere work for us as our calorimeter.

In the early 1960s, it was suggested that cosmic photons at energies of $\sim$1 TeV from point sources could be detected via Čerenkov radiation, produced by the $e^- e^+$ particle airshowers which they initiated in the atmosphere. The main drawback of this method for the study of $\gamma$-rays was the huge background of airshowers produced by charged cosmic rays. It was essential to be able to discriminate between the two classes of primary particles. Success came in 1989 with the introduction of the Čerenkov imaging technique, by which the Crab Nebula, the remnant of the supernova of AD 1054, was firmly established as a source of TeV $\gamma$-rays. Current atmospheric Čerenkov detec-
tors operate either by imaging, as described here, or by wavefront sampling.

Almost a century after their discovery, the origin of hadronic cosmic rays remains a mystery. Their arrival directions at Earth provide no clue as to their source since their paths are contorted by galactic magnetic fields; they form an apparently isotropic background for Čerenkov telescopes. The hadronic cosmic ray distribution throughout the galaxy should be traceable through their interactions with matter and subsequent γ-ray emission, for example via π° decay. The remnants of supernova explosions are generally believed to supply the cosmic ray particles of energies up to $Z \times 10^{14}$ eV in our galaxy, since little else could provide sufficient energy. Such objects are therefore prime targets for VHE γ-ray astronomers seeking the cosmic ray accelerators.

Less than 1% of the VHE γ-ray sky has been mapped by the most sensitive means and there are about a dozen recognised VHE γ-ray sources. Some are active galaxies, which emit dramatic flares during which the count rate of VHE γ-rays doubles on a timescale of hours. The γ-ray luminosity and flare timescale, together with near simultaneous X-ray and optical emission episodes, allow us to estimate the magnetic field strength and Doppler factor at the source, indicating emission from highly relativistic plasma jets.

2 The Imaging Atmospheric Čerenkov Technique

Typically about 0.01% of the energy of an incoming cosmic γ-ray is expected to be dissipated as Čerenkov light. This illuminates a disc of radius $\sim 125$ m on the ground for the $\sim 10$ ns equivalent to the lifetime of the particle shower. In essence, an atmospheric Čerenkov telescope acts as a “light bucket”, a single mirrored dish which reflects a fraction of the Čerenkov light pool onto a camera in the focal plane.

2.1 Telescope Construction

The largest single dish now in operation is the 10 m diameter telescope at the Whipple Observatory in Arizona, shown in figure 1. This will be surpassed by the 17 m diameter MAGIC Telescope in the latter half of 2001. Atmospheric ozone absorbs much of the UV component of the Čerenkov flash so that the light intensity peaks at around 300 nm, for which a high reflectivity can be achieved with an anodized aluminium coating on a glass or lightweight aluminium substrate. Current telescopes use cameras of several hundred close-packed photomultiplier tubes to record images of the Čerenkov light flashes. These are digitized and subsequently parameterized in terms of brightness, shape, orientation and angular position. The ability to derive an arrival di-
rection, primary energy and primary particle type ($\gamma$-ray, cosmic ray nucleon or local muon) from these images is dependent upon both the accuracy of our models of high energy particle cascade development, and our knowledge of the variable state of the calorimetric volume of atmosphere above the telescope.

2.2 Nature’s Challenges

Čerenkov telescopes are pointed instruments viewing a few square degrees of sky. $\gamma$-rays from an astronomical object are expected to produce compact Čerenkov images pointing towards the position of that object in the field of view. Cosmic ray induced airshowers develop sub-showers as a result of the relatively high transverse momentum of hadronic daughter particles and should therefore produce identifiably irregular Čerenkov images. When attempting to lower a telescope’s energy threshold, by reducing the threshold light level for an event to be recorded, individual muons created in hadronic showers which reach the level of the detector (as seen in figure 2) can mimic $\gamma$-ray events. Whilst the Čerenkov light ring from a muon striking the centre of the mirror is clearly recognisable (in figure 3), a small “muon arc” image will be recorded if the impact point is several metres from the telescope. One
Figure 2. Simulated air showers initiated by vertical 1 TeV γ-ray (left) and proton (right) primaries. Few particles reach the altitude of the Whipple Observatory (dashed line).

Figure 3. Čerenkov events recorded by the Whipple Telescope attributed to a γ-ray (left) and a single local muon (right). Filled circles scale with no. of ADC counts in a channel.

A further source of background noise events is quite simply the fluctuating brightness of the night sky. This can instantaneously result in two or three random photomultiplier signals above the fixed discrimination threshold. One way to eradicate this background is to require that a γ-ray like image has been simultaneously observed by multiple telescopes tracking the same astronomical object.
threshold, triggering the recording of a false event. A programmable hard-
ware trigger has been developed for the Whipple Telescope which can identify
candidate Čerenkov events with adjacent pixel signals within 65 ns.

Dealing with background light is further complicated by bright stars in
the field of view. As objects are tracked across the sky the movement of the
telescope places a variable strain on cables and connectors. These must also
withstand diurnal and seasonal temperature changes, humidity, wind and an
occasional loading of snow at high altitudes. Where necessary control connec-
tions are made over optical fibre to reduce the likelihood of lightning damage.
Prototype, low cost, analogue fibre optic links have been developed to trans-
mit photomultiplier signals to data acquisition electronics on the ground. These
introduce far less signal dispersion than co-axial cable. Keeping the
pulse width narrow allows one to reduce the integration time and hence the
amount of night sky background noise included with the Čerenkov signal. The
use of FADCs for charge digitization can provide not only a better esti-
mate of instantaneous background light levels, but also some information on
the time structure of each pulse, a characteristic of the airshowe r’s develop-
ment and hence a potential clue to the primary particle type.

3 Cosmic Particle Accelerators

3.1 Galactic VHE $\gamma$-ray Sources

The non-thermal radiation from the Crab Nebula supernova remnant is well
documented from radio wavelengths through to VHE $\gamma$-rays. It is supposed
that the central neutron star spinning at 30 Hz is generating a pulsar wind of
relativistic electrons. The spectrum, shown in figure 4 is dominated b y the
interactions of these electrons with the magnetic fields in the gaseous nebula
and ambient photon fields. Synchrotron emission can account for the curve
from the radio through to satellite $\gamma$-ray observations by COMPTEL and
EGRET at up to 1 GeV. The corresponding electron energies required are from
10 GeV to 100 TeV as indicated. The VHE $\gamma$-ray emission is fitted by a second
component (dashed curve in figure 4), due to the inverse Compton scattering
of soft photons up to energies above 10 TeV by relativistic electrons. Effective
acceleration of particles to beyond $10^{14}$ eV is implicit. Given the electron
spectrum required to generate the VHE $\gamma$-ray flux, a local magnetic field
strength of $\sim$16 nT was deduced from the observed level of X-ray synchrotron
emission presumed to be due to these same electrons.

There have been three tentative detections of VHE $\gamma$-rays from shell-
type supernova remnants which lack a central neutron star dynamo. X-ray
observations of one of these objects, SN1006, indicate synchrotron emission from electrons with energies of $\sim100\text{ TeV}$. The $\gamma$-ray flux can therefore be accounted for without invoking $\gamma$-ray production as a result of collisions between relativistic protons and the interstellar medium (principally atomic hydrogen) e.g. according to $p + ISM \rightarrow \pi^0 + X \rightarrow \gamma + \gamma + X$. There is still no firm evidence for hadronic cosmic ray production at supernova shock fronts.

3.2 $\gamma$-ray Sources at Cosmological Distances

There are two well-established sources of VHE $\gamma$-rays outside our own galaxy, objects known as Markarian 421 and Markarian 501. These are both blazar type active galaxies, at a distance of some 500 million light years, in which gravitational accretion of matter onto a central supermassive black hole is assumed to be powering an outflow of material in relativistic plasma jets. The rapid variability and high luminosity of the VHE $\gamma$-ray flux from these objects seems to indicate that the $\gamma$-rays are relativistically beamed. Our line of sight to each must therefore be such that we happen to be looking straight down one of the jets. For the 15 minute timescale VHE $\gamma$-ray variability observed from Markarian 421, causality implies an emission region as small as our solar system.  

The multi-wavelength spectra of Markarian 421 and Markarian 501 conform quite well to the two component synchrotron plus electron inverse Compton fits of synchrotron and inverse Compton components by Aharonian and Atoyan.
ton scattering mechanism proposed for the Crab Nebula. Correlated episodes of enhanced emission of $\gamma$-ray and optical/UV photons imply that these photons are produced in the same region of the jet. In this case, jet Doppler factors in the range of $2 < \delta < 40$ are required to avoid a significant loss of VHE $\gamma$-rays to pair production with the low energy photons. If the VHE $\gamma$-rays in fact result from hadronic cascades produced by high energy protons in the jet, as proposed by Mannheim and others, then $\delta \approx 10$.

The cosmic infrared background (CIB) traces the history of star formation and galaxy evolution in the early universe. VHE $\gamma$-rays from active galaxies can provide a means of probing the CIB. The $\gamma$-ray signal will be attenuated by pair production: $\gamma_{VHE} + \gamma_{IR} \rightarrow e^- + e^+$. Since the attenuation becomes more significant as the $\gamma$-ray energy increases, we expect to see a distance dependent, high energy cut-off in the VHE spectra of active galaxies. Upper limits on the CIB which are more restrictive than direct measurements in the 0.025 to 0.3 eV range have already been obtained. To establish whether spectral cut-offs are due to this effect or are in fact intrinsic to these objects more sensitive instruments are required to extend the source catalogue.

4 Next Generation Telescopes

Several “next generation” atmospheric Čerenkov observatories are under construction. VERITAS in Arizona, HESS in Namibia and CANGAROO III in Australia will be arrays of 10 m diameter class imaging Čerenkov telescopes. By viewing each airshower with several telescopes separated by about 100 m, greatly improved angular and energy resolution and an increased collection area will be achieved between 100 GeV and 10 TeV. As a single 17 m diameter dish, the MAGIC Telescope, on the Canary Island La Palma, will have the lowest energy threshold of 30 GeV using a standard photomultiplier camera, or 15 GeV if equipped with hybrid GaAsP photocathode photodetectors.

4.1 Fundamental Physics

The greater sensitivity of the planned instruments will improve the chances of new detections of active galaxies, the pulsed signatures of objects such as the Crab pulsar and $\gamma$-ray bursts. Their angular resolution should enable us to identify some of the 170 sources detected with large position errors by the EGRET satellite instrument. In addition, VHE $\gamma$-ray observations may improve our view of some fundamental physics phenomena.

Our current understanding requires the presence of cold dark matter in the universe to explain certain astrophysical data. The neutralino is a favoured
dark matter candidate. A concentration of neutralinos towards the centre of our galaxy may produce a detectable monoenergetic annihilation line in the neutralino mass range of 30 GeV to 3 TeV.

γ-ray observations of distant objects can be searched for the effects of quantum gravity. The velocity of light may exhibit an energy dependence due to quantum fluctuations in a gravitational medium, resulting in a time dispersion within VHE γ-ray flares. A 15 minute flare from Markarian 421 has already been used to place a limit on this effect, which could be vastly improved by instruments sensitive to minute by minute variability.

Low mass black holes, remnants of inhomogeneities in the early universe, should emit a burst of radiation peaked at around 1 TeV in the final stages of their evaporation, according to Halzen et al. In fact, the predicted time profile and energy spectrum depend on whether one follows the standard or bootstrap models for the particle spectrum at high energies.

These are just a few of the topics in particle physics and astrophysics which the next generation of imaging Čerenkov telescopes may address. I would like to thank all involved in this Symposium for their encouragement!

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