Gamma Ray Astronomy (WG I): Science Results

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Abstract. TeV astronomy is currently dominated by Very High Energy\(^1\) (VHE) \(\gamma\)-ray observations using a new generation of ground-based atmospheric Cherenkov telescopes. A few years of data taking with these instruments have yielded a spectacular view of the universe, probing some of the key science questions in high energy astrophysics today. TeV \(\gamma\)-ray observations may be pivotal in solving the question of the origin of cosmic rays, in understanding the physics of relativistic jets and their connection to black holes, may help us in dissecting different contributions to the diffuse \(\gamma\)-ray emission from the galactic plane and provide prospects for astrophysical dark matter detection. The interpretation of extragalactic VHE \(\gamma\)-ray sources is complicated by appreciable absorption off intergalactic diffuse radiation known as the Extragalactic Background Light (EBL). Attenuation features in TeV spectra of extragalactic sources due to the EBL provide an important link to optical/infrared astronomy and Cosmology.

VHE \(\gamma\)-ray astronomy is spearheading the TeV sky and has advanced our understanding of physical parameters in astrophysical sources at the highest energies through major improvements in the imaging capability and time resolved spectroscopy with the imaging atmospheric Cherenkov technique. Many aspects of the science questions addressed by TeV \(\gamma\)-ray observations will undoubtedly have consequences for neutrino astronomy in the next decade. This paper provides a brief summary of the scientific results and observations reported at the Working Group on Gamma Ray Astronomy at this conference.

1. Introduction
The field of TeV gamma-ray astronomy was pioneered by the Whipple collaboration with the first detection of TeV photons from the Crab nebula in 1989 \cite{1}. The birth of extragalactic TeV astronomy came with the subsequent surprise discovery of TeV blazars, as they had not been anticipated in astrophysical theory. Towards the end of the 1990s the TeV \(\gamma\)-ray source catalog contained four gamma-ray blazars and the Crab nebula. Persistent searches by several atmospheric Cherenkov groups (HEGRA, CAT and Whipple) revealed a few more sources with 2nd generation imaging Cherenkov telescopes yielding weak detections including the supernova remnant Cassiopeia A \cite{2} and the radio galaxy M87 \cite{3}.

The potential of third generation of imaging atmospheric Cherenkov telescopes had become apparent by the mid 1990s and proposals were submitted in the US, Europe and Japan. The first of those new systems are now online: HESS started operation with four telescopes in Namibia in 2004, MAGIC in 2004 with one large telescope in La Palma and VERITAS-4 is expected to be online by early 2007 in southern Arizona. Select results from the first few years of observing were reported at this conference and are summarized in the following along with complementary

\(^1\) Energies between 100 GeV and 100 TeV are typically referred to as the VHE regime of \(\gamma\)-ray astronomy.
results from a wide angle water Cherenkov detector, the Milagro observatory. Although the sky at VHE energies covers now a wealth of astrophysical phenomena, the unequivocal detection of Gamma Ray Bursts (GRBs) has been elusive. In that context recent results from the Swift telescope and theoretical studies reemphasize the prospects for the detection of VHE $\gamma$-rays from GRBs [4], [5].

2. Galactic Sources
Perhaps the most striking result of TeV astronomy after a few years of observations with third generation telescopes is summarized by the sky map shown in Fig. 1, of the inner galactic plane produced by the HESS collaboration. The galactic center, plerions, shell-type supernova remnants, an X-ray binary, a microquasar, and several unidentified sources cluster around the galactic plane. It has become clear that imaging atmospheric Cherenkov telescopes with a field of view of $\approx 5^\circ$ are well suited for a survey of our galaxy with good angular resolution and a sensitivity of 1% of the Crab flux.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{inner_galactic_plane.png}
\caption{A view of the inner galactic plane out to longitudes of 35$^\circ$ and 335$^\circ$ TeV $\gamma$ rays [6].}
\end{figure}

The wealth of scientific results reported at this workshop combined with the advancements in the imaging and spectroscopic capabilities of the imaging atmospheric Cherenkov technique require me to focus on a select number of topics for this review, for more details on all the results see [6], [7], [4], [8], [9] and references therein.

2.1. Supernova Remnants
The detection of VHE $\gamma$ rays from supernova remnants may be the key to understanding their role in producing the galactic cosmic-ray component [10]. The HESS collaboration reported the detection of several shell-type supernova remnants [6]. The most detailed and morphological study presented is concerned with RX J0852.0-4622 also known as “Vela jr.” (Fig. 2) and RX J1713.7-3946 (Fig. 3) both showing resolved shell features in TeV photons. The angular resolution of the imaging atmospheric Cherenkov technique and the field of view of the HESS telescopes provide sufficient imaging capability for resolving RXJ1713.7-3946 and “Vela jr.” which are 1$^\circ$ and 2$^\circ$ across.

Both objects exhibit non-thermal X-ray emission suggesting the presence of highly relativistic electrons that could also produce TeV emission. A comparison of the structure of the TeV image of “Vela jr.” with the corresponding X-ray image [6] from ROSAT and ASCA shows a 2

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{vela_jr.png}
\caption{Stereoscopic imaging of showers using atmospheric Cherenkov telescopes provides an angular resolution of 0.05$^\circ$ – 0.1$^\circ$ for individual gamma rays depending on the primary energy.}
\end{figure}
correlation at the 70% level. Similar correlations are observed for RXJ 1713.7-3946. The similar
morphology in X-ray and TeV γ-ray emissions is consistent with models in which the emissions
have a common origin: relativistic electrons emit synchrotron radiation in X-rays and inverse
Compton scatter ambient soft photons to TeV energies. In the case of “Vela jr.” the X-ray and
TeV data can be fit by an IC model [6], when using a magnetic field comparable to that of the
galactic plane.

The case of RXJ1713.7-3946 is complicated by the fact that it is associated with dense
molecular clouds along the line of sight and that the TeV emission appears to correlate with
the gas density. It may be suggestive that part of the TeV emission traces regions of a high
gas density hinting that the γ ray emission originates in part from the decay from neutral pions
produced in cosmic-ray interactions with interstellar gas. The HESS collaboration finds that a
hadronic model fits the data better than leptonic models [6], however, it is also made clear that
no unequivocal statement about the nature of the γ-ray emission mechanism can be claimed at
this point.

More observations are necessary to discriminate between hadronic and leptonic origin: and
the combined spectra from ground-based telescopes and the Gamma-ray Large Area Space
Telescope (GLAST) covering GeV [11] to TeV energies are critical. In hadronic models the hard
spectra observed at TeV energies extend to GeV energies whereas in leptonic models the inverse
Compton peak softens towards lower energies. Nevertheless, TeV telescopes provide for the first
time sufficient sensitivity and angular resolution for morphological and spectral studies to test
the paradigm that cosmic rays are accelerated in supernova remnants. This matter is largely
complicated by the presence of relativistic electrons: energy spectra from X-ray observations,
high energy and VHE γ-ray telescopes are required to discriminate between hadronic and leptonic
origin.

Finally, it is important to mention that imaging Cherenkov telescopes have the capability
to perform spectroscopic imaging: spatially varying energy spectra in the pulsar wind nebula
G18.0-0.7 were reported by the HESS collaboration indicating the cooling of electrons as they
propagate further out in the nebula. This could also potentially proof an important tool for
resolving emission components in extended sources associated with different particle populations.

2.2. Microquasars
Microquasars constitute a subclass of X-ray binaries and exhibit relativistic outflows of plasma
from their compact object, either a neutron star or stellar-mass black hole. Microquasars offer
a closeup view of a jet emening from a compact object and allows one to perform detailed
measurements of the jet emission as it passes through the radiation field of the companion star in a periodic and well defined sequence. This may be useful in understanding, which particle species dominate in the jet and may constrain the magnetic field strength, jet geometry and may provide clues as to how jets are launched and collimated.

Both the MAGIC and the HESS collaboration reported the detection of a microquasar at TeV energies, LS 5039 [6] and LS I+61° 303 [9]. Both objects exhibit TeV γ-ray flux variations. In fact, phase resolved spectroscopy of LS5039 shows that the energy spectra at the inferior and superior conjunction are substantially different (see Fig. 4 and Fig. 5).

![Figure 4](image1.png)

**Figure 4.** Basic geometry of a microquasar in different orbital phases and the implications for γ-ray absorption are shown.

![Figure 5](image2.png)

**Figure 5.** The energy spectra of LS 5039 at two different phase intervals are shown.

The flux values of LS 5039 at the two orbital positions are similar at 200 GeV, but towards higher energies substantial absorption occurs when the compact object passes through the superior conjunction. This is the first time that spectral attenuation from $\gamma_{\text{soft}} + \gamma_{\text{TeV}} \rightarrow e^+ + e^-$ by an ambient photon field in an astrophysical source has been observed. The absorption of TeV γ rays can be a useful tool for constraining the TeV emission region. For example in case of LS 5039 it allows to provide constraints on the location of the γ-ray emission region to within 1 AU from the binary system and the modulation with the phase also allows to set a limit to the size of the emission region to be less than the separation between the compact object and the massive companion star. Further constraints may be possible in particular for determining whether or not the emission has its origin in hadronic or leptonic. Phase resolved studies of a jet source orbiting a massive companion star offers a new set of observables to study relativistic jets.

### 2.3. Diffuse Emission from the Galactic Plane and from the Cygnus Arm

The detection of diffuse γ-ray emission with ground-based telescopes is a difficult task considering the enormous background from cosmic-ray showers. The galactic plane emission detected with EGRET exhibits an unusually hard spectrum known as the "GeV excess" leaving a challenge to TeV γ-ray astronomy. Extending the energy spectrum into the TeV regime will illuminate this subject. The report of diffuse TeV γ-ray emission along the galactic plane by Milagro provides a first step. The brightest region is centered around the Cygnus arm, a spiral arm within our galaxy at $l = 75^\circ$ showing a $12\sigma$ excess. The TeV flux is strong with $\approx 2$ Crab [8] and could have different origins: the Cygnus arm is a rich and complex region containing supernova remnants, OB associations and Wolf Rayet stars. Resolving the point sources with the imaging atmospheric Cherenkov telescopes should give us a better understanding of the origin of this excess and its connection to the diffuse component.
Figure 6. A view of the galactic plane around $l = 25^\circ$ and $l = 90^\circ$.

Diffuse $\gamma$-ray emission from the galactic plane is related to the cosmic ray distribution and diffusion in the galaxy, is a tracer of relativistic electrons [12] and could also contain secondary emission components from dark matter annihilation [13]. The large scale structure of the diffuse component and resolving the point source component is a pressing topic in future observations with GLAST and the ground-based telescopes.

3. Extragalactic TeV Observations

The TeV source catalog contains at least 13 extragalactic objects, all of them are blazars except one, the nearby ($z=0.0004$) radio galaxy M87. Blazar observations provide a high energy perspective of relativistic jets with the jet pointing towards the observer. The jet axis of the radio galaxy M87 is seen at an angle of $30^\circ - 40^\circ$ allowing morphological studies of the side on view of the jet in the radio, optical and X-ray wavebands. Recent studies of M87 by HESS [7] indicate variability on time scales of less than 1 year and challenge emission models that involve a large scale jet and Dark Matter scenarios.

Reports of VHE observations of blazars at this meeting were concerned with flux variability, constraining the jet emission models and energy spectra addressing absorption by the EBL. Flux variations as short as 5 minutes were reported by the MAGIC collaboration [9] and by HESS. A strong flare of PKS2155-304 [7] showed again flux levels of multiple times the Crab as seen before for Mrk 421 and Mrk 501 reminding us that blazars are the brightest TeV sources in the sky. These data together with contemporaneous campaigns at X-ray energies are sensitive probes of jet emission models often indicating X-ray/TeV $\gamma$-ray correlations. Spectral variations at TeV energies are also promising tests for emission models and in probing the persistence of putative features imprinted onto the spectra by the absorption of $\gamma$ rays by the EBL.

The TeV blazar list spans redshifts between $z=0.03$ and $z=0.186$ allowing to test EBL absorption scenarios. Spectral measurements of 1ES 1101-232 combined with theoretical constraints of the intrinsic spectra of blazars indicate that the EBL between 0.8$\mu$m and 3$\mu$m is low [7] and close to the lower limits from galaxy counts. These results are not inconsistent with previous results by [14]. However, it should be noted that the conclusion about a low EBL density relies on assumptions about the intrinsic source spectra, which is theoretical in nature. The detection of PG 1553 is tantalizing since the redshift is largely uncertain but believed to be at least $z=0.36$ indicating that perhaps the universe more transparent to TeV $\gamma$ rays than previously thought.

3.1. Prospects for TeV Detection of GRBs

The search for GRBs at TeV energies has not yielded a convincing detection yet [8], [9]. Due to the large distance of most GRBs, absorption by the EBL is an obstacle to putative TeV components. Low energy threshold/wide field of view instruments are required for detecting the
prompt component from a GRB. An instrument with both virtues does not exist in the VHE regime to date. The detection of X-ray flares 100s of seconds after the prompt burst may be promising for detecting GRBs with low threshold imaging atmospheric Cherenkov telescopes (VERITAS [15], HESS [16], MAGIC [17] or CANGAROO [18]). Wide field of view detectors with a high energy threshold such as Milgaro could see the prompt emission, if the GRB occurs sufficiently nearby. For further details see [4] and [5].

4. Outlook and Conclusions
TeV γ-ray astronomy has progressed at a rapid pace over the last few years probing the origin of cosmic rays in our galaxy through morphological and spectral studies of supernova remnants. The new third generation instruments scrutinize a variety of galactic sources for their TeV γ-ray emission mechanism, potentially providing clues about hadronic acceleration sites in our galaxy. The study of relativistic jets at TeV energies has been enriched by two new types of objects: microquasars and a nearby radio galaxy M87. In microquasars, the orbital motion of the compact object and its jet moving in the radiation field of a massive companion star is a unique laboratory for understanding how jets are launched at a black hole, how they are collimated and what they are made of. Diffuse TeV emission from the galactic plane provides a first glimpse of how TeV astronomy can probe and untangle the different emission mechanisms linked to the cosmic-ray and electron distribution and possible implications on dark matter annihilation in the galaxy. A key question for extragalactic VHE γ-ray astronomy is related to the transparency of the universe. Recent detections of blazars indicate that the universe is more transparent than previously thought. This increases the number of detectable extragalactic sources for VHE γ-ray astronomy including nearby GRBs assuming they emit TeV radiation.

Acknowledgments
The author acknowledges support from the U.S. Department of Energy and also thanks the organizers for the invitation to this excellent conference.

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