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Gamma-Ray Astronomy

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Abstract. The relevance of gamma-ray astronomy to the search for the origin of the galactic and, to a lesser extent, the ultra-high-energy cosmic rays has long been recognised. The current renaissance in the TeV gamma-ray field has resulted in a wealth of new data on galactic and extragalactic particle accelerators, and almost all the new results in this field were presented at the recent International Cosmic Ray Conference (ICRC). Here I summarise the 175 papers submitted on the topic of γ-ray astronomy to the 30th ICRC in Merida, Mexico in July 2007.

Introduction

This paper reports on the results from the sessions OG 2.1–2.4 of the 30th ICRC. These sessions covered topics related to the origin of cosmic rays (CRs) as probed by γ-ray and X-ray measurements. In fact very few papers concerned purely with X-ray measurements were presented and so for simplicity I will discuss only the results involving γ-rays here. The classifications are defined as follows:

- OG.2.1 Diffuse X-ray and gamma-ray emission
- OG.2.2 Galactic sources (Binaries, pulsars, SN remnants, etc.)
- OG.2.3 Extra-galactic sources (AGNs, Quasars, Gal.clusters, etc.)
- OG.2.4 Gamma-ray bursts

A total of 175 papers (including presentations and posters) where submitted under these four sections, the vast majority (144) under OG.2. and OG.2.3. There was also a predominance of contributions from experimental collaborations involved with ground-based γ-ray astronomy (123/175). I will therefore focus in this summary on experimental results in TeV γ-ray astronomy. Indeed, essentially all recent results in the γ-ray field were presented at this conference. This is natural if one follows the broadest possible definition of cosmic rays as simply "astrophysical relativistic particles": $\geq$ GeV γ-rays can *only* be produced by CRs. Conversely, it is increasing recognised that γ-ray measurements provide a powerful tool for studying the acceleration and propagation of CRs of all energies.

After a brief summary of the instrumentation available for γ-ray astronomy I will present my personal selection of highlights in each of the sections listed above. I apologise in advance to everyone whose work I have unfairly omitted and to all whose work I may inadvertently misrepresent.

Experimental Status

Although the sessions OG 2.1 - 2.4 effectively cover only the results from γ-ray detectors and not the status of these instruments, it is useful to begin with a summary of the existing instrumentation and the advantages and short-comings of different approaches. For the moment, there is a clear division in the field between measurements in the roughly 0.1–10 GeV range (High energy or *GeV* measurements) made with satellite based instrumentation and roughly 0.1–100 TeV (very high energy, VHE, or *TeV*) measurements made with ground-based instruments. A real overlap between these domains will very likely be established within the next few years, but for now they can be considered separately:

GeV

After a period of relative quiet, the GeV field is now increasingly active as a consequence of the planned launch of the GLAST satellite early in 2008 and the recent launch of AGILE. The upcoming new instrumentation has prompted several authors to revisit the data of the EGRET instrument (1991-2000). Perhaps, the most significant of these new analyses is the production of a new catalogue after modified analysis and in particular modified diffuse background subtraction [1]. The new 3GR catalogue contains 23 new sources, but 121 third EGRET catalogue sources are not found in the new analysis. Whilst this new analysis is controversial, there are certainly indications that diffuse γ-ray background uncertainties are such that the positions and even existence of many 3EG sources are very uncertain. Whilst the better angular resolution and sensitivity of GLAST with respect to EGRET will certainly help with source identification, it is clear that understanding the diffuse background is crucial to the success of GLAST for galactic astrophysics. A major effort is underway in the GLAST collaboration to improve models for the diffuse emission based on CR transport and tracers for atomic and molecular target material and radiation fields [2, 3]. Amongst the presentations on the scientific potential of GLAST were reviews of expectations for blazar measurements [4] and for detections of pulsars [5], pulsar wind nebulae and supernova remnants [6], and for GRBs [7] and also possibilities for more exotic phenomena such as inverse Compton halos around massive stars [8].

The relationship between sources at GeV and TeV energies was discussed by several authors. A systematic comparison based on the region of the H.E.S.S. galactic plane scan showed essentially no evidence for correlation between the H.E.S.S. and 3EG catalogues [10, 11]. The lack of sensitivity of EGRET seems to be a major factor in the non-detection of TeV sources and GeV energies, whereas the existence of spectral breaks (or cut-offs) is likely required to explain the missing GeV sources at TeV energies. Another complicating factor in the comparison of GeV and TeV data is the mismatch in field-of-view and angular resolution for existing measurements. The possibility that some 3EG sources are perhaps rather extended and hence difficult to detect with narrow field-of-view Cherenkov telescopes was raised by the MILAGRO collaboration (MILAGRO has a very wide field of view and modest angular resolution). Indeed, there are hints of a connection between the new MILAGRO sources and 3EG/GeV sources [12], but without better angular resolution measurements, the problems of source identification will likely remain.

The AGILE satellite, a relatively small area, but wide field of view instrument, was launched in April 2007. The energy range and overall sensitivity of AGILE are comparable to EGRET, but its wider field of view makes it particularly suitable for the monitoring of blazars, and it could prove useful as a trigger for TeV instruments [13].

TeV

Ground-based techniques for γ-ray astronomy rely on the development of cascades (air-showers) initiated by astrophysical γ-rays. Such cascades only persist to ground-level above $\sim$1 TeV and only produce significant Cherenkov light above a few GeV, setting a fundamental threshold to the range of this technique. Ground-based measurements in the $\sim$50 GeV to $\sim$100 TeV range have resulted in a exponential increase in the number of sources known to emit in this energy range over the last few years. This progress is compared to that in other energy ranges in figure 1, an updated version of a plot due to Tadashi Kifune. Two principal approaches to such measurements exist and this are considered here in turn.

Cherenkov Telescopes

The most successful approach to ground-based γ-ray astronomy is that based on the imaging of the Cherenkov light produced by photon initiated cascades in the Earth's atmosphere. These relatively small field-of-view instruments ($\sim$4°) have $\sim$10% duty cycle due the need for good weather and complete darkness, but achieve angular and energy resolution much better than that of any other ground-based γ-ray technique ($\sim$0.1° and $\sim$15% respectively). The success of this technique also results from the ability to reject a large fraction of the cosmic-ray background based on the shape of the Cherenkov images (see for ex-

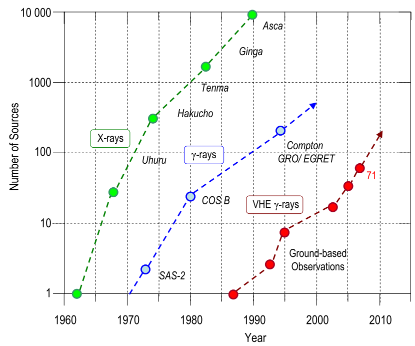

Fig. 1. Source numbers versus time in the X-ray, high-energy γ-ray and VHE γ-ray domains (adapted from a plot by Tadashi Kifune). VHE source counts plotted are those reported by rapporteurs at each international cosmic ray conference.

ample [14]). The use of multiple Imaging Atmospheric Cherenkov Telescopes (IACTs) to allow stereoscopic reconstruction of the shower provided a further breakthrough in sensitivity and resolution. The existing Cherenkov telescopes and telescope arrays are summarised in table 1. Three multiple-telescope arrays of IACTs are currently operating: VERITAS [15], CANGAROO-III [16] and H.E.S.S.

H.E.S.S. is a four telescope array located in the Khomas highlands of Namibia. The latitude of H.E.S.S., its relatively wide field of view (5°) and its unprecedented sensitivity (0.7% of the flux from the Crab Nebula at 5σ in 50 hours of observations) make it an ideal instrument to survey the galactic plane. Indeed, the ongoing H.E.S.S. galactic plane survey has led to a dramatic increase in the number of galactic TeV sources [17].

The recently completed (April 2007) VERITAS array is rather similar to H.E.S.S. in several respects and can be considered as a complementary northern hemisphere instrument. Despite its recent completion VERITAS has already produced several important results (summarised in [15]).

CANGAROO-III consists of three new telescopes deployed around the single CANGAROO-II telescope in Australia. Some controversy surrounded certain sources detected using CANGAROO-I and -II and subsequent non-detections using H.E.S.S. As of this conference none of these disagreements remain following more sensitive observations with CANGAROO-III and resulting retraction of some earlier results [16]. In addition CANGAROO-III has been used to confirm some of the discoveries using H.E.S.S. [18, 19].

The 17 m diameter MAGIC telescope on La Palma represents the state-of-the-art in terms of single dish instruments. The instrument is optimised for low energy measurements and has had considerable recent success in discovering steep spectrum extragalactic sources.

Following the success of H.E.S.S. and MAGIC, both instruments are in a second phase of construction. For H.E.S.S. this involves the construction of a 600 m^2 telescope at the centre of the existing array, with the aim of achieving useful sensitivity in the unexplored $<$50 GeV region. MAGIC phase-2 consists of the construction of a second 17 m diameter telescope with the aim of using stereoscopic techniques to improve sensitivity and reduce threshold.

Useful contributions are also being made using instruments of more modest sensitivity such as TACTIC [20] and the long serving Whipple 10 m telescope [21]. Both these instruments are being used to monitor the brightest TeV blazars and can be used to alert more sensitive instruments.

In addition to these imaging telescopes, several groups have made use of non-imaging Cherenkov telescopes, these include the PACT array and several groups making use of modified solar power facilities. The enormous available mirror area of these facilities can be used at night to conduct air-Cherenkov based γ-ray measurements. The CELESTE, STACEE, Solar-2, CACTUS and GRAAL collaborations all pursued this concept and were largely successful in achieving low ($<$100 GeV) energy thresholds but unfortunately their discovery potential was limited by relatively poor background rejection capabilities (in comparison to imaging techniques). To my knowledge none of these instruments is still operational. The final results from the recently decommissioned STACEE instrument were presented here.

Shower Particle Detectors

The depth of maximum development of photon initiated air-showers typically occurs close to 10 km

Instrument	Lat. (°)	Long. (°)	Alt. (m)	Tels.	Tel. Area (m^2)	Total A. (m^2)	Pixels	FoV (°)	Thresh. (TeV)
H.E.S.S.	-23	16	1800	4	107	428	960	5	0.1
VERITAS	32	-111	1275	4	106	424	499	3.5	0.1
MAGIC	29	18	2225	1	234	234	574	3.5†	0.06
CANGAROO-III	-31	137	160	3	57.3	172	427	4	0.3
Whipple	32	-111	2300	1	75	75	379	2.3	0.3
Shalon	43	77	3338	1	11.2	11.2	144	8	0.8
vvvTACTIC	25	78	1300	1	9.5	9.5	349	3.4	1.2
HEGRA	29	18	2200	5	8.5	43	271	4.3	0.5
CAT	42	2	1650	1	17.8	17.8	600	4.8†	0.25

Table 1. Principle characteristics of currently operating (and selected historical) IACTs and IACT arrays. The energy threshold given is the approximate trigger-level (rather than post-analysis) threshold for observations close to zenith. † These instruments have pixels of two different sizes.

a.s.l. for 1 TeV γ-rays. However, the tail of the shower is detectable far past maximum for detectors with sufficient collection area. These instruments achieve duty-cycles close to 100% and $\sim$1 sr field-of-view (FoV), but have modest angular and energy resolution ($\sim$1° and $\sim$50% respectively). Two approaches exist for γ-ray measurements via direct sampling of the shower particles. The classical method is to use an array of (relatively) widely spaced scintillator-based detectors. The Tibet ASγ instrument employs this approach at high altitude (4300 m) to reduce the energy threshold to $\sim$3 TeV. The second approach requires complete coverage of the ground to ensure efficient collection of shower particles and hence lower energy threshold. The recently completed ARGO-YBJ detector [26] at the Tibet site is a solid-state detector following this approach. Arguably the most successful shower-particle detector built for γ-ray astronomy is MILAGRO, a water-Cherenkov based instrument at Los Alamos (2630 m altitude). This instrument has been operating for 7 years, but recent detector and analysis improvements have led to the significant detection of 4 sources including 3 new discoveries [12]. The new analysis cuts significantly improve background rejection power, but at the expense of increased energy threshold (to $\sim$20 TeV from a trigger threshold of $\sim$1 TeV). The MILAGRO instrument is nearing the end of its operational life, but plans for a follow-up instrument built at much higher altitude are well advanced [27, 28]. The High Altitude Water Cherenkov (HAWC) instrument should reach significantly lower energies and better sensitivity whilst maintaining the advantages of high duty cycle and FoV.

During the 1990s several more widely spaced ground arrays were constructed to search for $\sim$100 TeV γ-rays. The very long exposures of these instruments partially compensates for the low γ-ray rates at these energies and the absence of significant background rejection capabilities. The upper limits presented by the CASA-MIA [29] and SPASE-2 [30] collaborations therefore lie at interesting flux levels. The GRAPES-III instrument is an intermediate case with a $\sim$ 10 TeV threshold [31].

OG 2.1: Diffuse Gamma-ray Emission

Particles (particularly protons and nuclei) of $\geq$ GeV energies, can readily propagate very large distances in the ISM without significant energy losses. As a consequence the emission associated with these energy losses is often rather diffuse. At GeV energies the γ-ray sky is dominated by the diffuse emission produced by galactic cosmic-rays in the ISM. At TeV energies it appears that the flux of the diffuse component is comparable with that from discrete sources [32]. This is unsurprising as the typical energy spectra of discrete sources lie close to the test-particle shock acceleration spectrum of E^{-2} (the mean photon index of sources found in the H.E.S.S. galactic plane survey was 2.3 [33]) and the spectrum of high energy γ-rays produced in hadronic interactions in the ISM approximately follows that of the incident protons and nuclei i.e.$E^{-2.7}$. The lower relative flux of the diffuse component and the small FoV of the most sensitive TeV instruments, make measurements of the galactic TeV diffuse emission very difficult. The only existing measurement of the (large-scale) diffuse TeV emission comes from the MILAGRO instrument [34] [1]. The MILAGRO collaboration have detected emission along the plane with localised enhancements which have been identified as sources. After subtraction of these sources the remaining emission roughly follows the distribution of target material in the galaxy and is identified as diffuse emission. The flux level of this emission lies about a factor two above the predictions of the GALPROP model [35] with parameters tuned to best reproduce the data from EGRET. As it seems very likely that there is still a significant contribution from discrete sources to this measurement, this level of agreement with predictions seems satisfactory.

The MILAGRO collaboration also presented the results of a search for intermediate scale (> 10 deg) features over the whole sky [36]. Significant anisotropies are indeed seen, but appear stronger in data without γ-ray selection cuts, suggesting they are charged particle anisotropies, perhaps related to the tail-in anisotropy seen using the Tibet ASγ instrument [37] (and as such lie beyond the scope of this summary).

OG 2.2: Galactic Sources

It is well established that the bulk of the cosmic rays measured at the Earth must originate within our own galaxy. As a consequence those CRs with energies up to at least 10^{15} eV are often referred to as the *galactic cosmic rays* (GCRs). The principal acceleration sites of the protons and nuclei of the GCRs are not yet well established. Indeed, although they make up a small fraction of the total energy in cosmic-rays, the origin of the electron component is equally unclear and important to establish.

It has long been recognised, see for example [38], that γ-ray measurements can aid in the identification of the CR acceleration sites in our galaxy. Two principal γ-ray production mechanisms are discussed here: The decay of neutral pions produced in hadronic interactions, which traces the product of ambient density and the density of CR protons and nuclei, and Inverse Compton up-scattering of ambient photon fields, tracing high energy electrons.

Although many TeV γ-ray sources are now known there are two major challenges to overcome to make progress in addressing the questions of cosmic-ray origin. The first and most basic is to identify γ-ray sources with counterpart objects at other wavelengths. This process can be far from straight-forward and many different techniques have been applied to provide solid source identifications. Table 2 lists the small fraction of galactic TeV sources with such identifications (note that the selection is somewhat subjective and the list given here is rather conservative). The second challenge is to infer the nature, and spatial and energy distributions of, the primary CRs. Differentiating between electrons and protons as the radiating particles has proved difficult, although several cases now exist where one or the other is strongly favoured.

Several of the sources in table 2 were discovered in the survey of the galactic plane conducted by the H.E.S.S. collaboration [33]. The extension of this survey to cover essentially the whole inner galaxy: $-85^\circ < l < 60^\circ, -2.5^\circ < b < 2.5^\circ$ is responsible for many of the new sources summarised here [17] (see figure 2). The positive galactic latitude extent of this survey is now limited by zenith angle constraints. The region inaccessible to H.E.S.S. has been covered by MILAGRO measurements and a survey of the Cygnus region with VERITAS is underway. It is to be hoped that by the time of the next ICRC a complete sensitive survey of the galactic plane will exist, allowing studies of the populations of galactic TeV sources. The current experimental situation already allows detailed studies of several classes of galactic object, and these are considered here in turn.

Supernova Remnants

Supernova remnants (SNRs) have long been the prime candidates for the acceleration of the bulk of the galactic cosmic ray protons and nuclei. They have sufficient energy, providing 10% of the kinetic energy of an average supernova explosion

1. a localised measurement of diffuse emission has been made in the Galactic Centre, see below

Object	Discovered	Year	Type	Method	Flux	Contrib.
PSR B1259−63	HESS	2005	Binary	Pos/Var	$7^{\star}$	[39]
LS 5039	HESS	2005	Binary	Pos/Per	$3^{\star}$	[40]
LS I +61 303	MAGIC	2006	Binary	Pos/Var	$16^{\star}$	[41, 42, 43]
RX J1713.7−3946	CANGAROO	2000	SNR Shell	Mor	66	[44]
Vela Junior	CANGAROO	2005	SNR Shell	Mor	100	
RCW 86	HESS	2007	SNR Shell	Mor	$\sim$10	[45]
Cassiopeia A	HEGRA	2001	SNR	Pos	3	[46]
Crab Nebula	Whipple	1989	PWN	Pos	100	[47, 48, 49, 50]...
MSH 15-52	HESS	2005	PWN	Mor	15	[51]
Vela X	HESS	2006	PWN	Mor	75	
HESS J1825−137	HESS	2005	PWN	EDMor	12	[52]
PSR J1420−6049	HESS	2006	PWN	Mor	7	
The Rabbit	HESS	2006	PWN	Mor	6	
G 0.9+0.1	HESS	2005	PWN	Pos	2	

Table 2. Galactic VHE γ-ray sources with well established multi-wavelength counterparts. The instrument used to discover the VHE emission is given together with the year of discovery. Fluxes are approximate values expressed as a percentage of the flux from the Crab Nebula above 1 TeV, * indicates variable emission. These associations were established through a range of methods, which are given in the table in abbreviated form: *Pos*: The position of the centroid of the VHE emission can be established with sufficient precision that there is no ambiguity as to the low energy counterpart. In practise this is usually only possible for point-like sources. *Mor*: There is a match between the γ-ray morphology and that seen at other (usually X-ray) wavelengths. This requires sources extended well beyond the typical angular resolution of IACTs ($\sim$0.1°). *EDMor*: Energy-dependent morphology which approaches the position/morphology seen at other wavelengths at some limit, and is consistent with our physical understanding of the source. *Var*: γ-ray variability correlated with that in other wavebands. *Per*: periodicity in the γ-ray emission matching that seen at other wavelengths. Note that all these objects have associated X-ray emission which has been interpreted as synchrotron radiation. Notable omissions from this table include Cyg X-1, IC 443 and W 28. These objects are discussed in detail in the main text.

can be converted into relativistic particles (see e.g. [38]), and there is a well established mechanism: diffusive shock acceleration in the SNR shell [53, 54]. Despite this, only rather recently has strong evidence for the acceleration of particles in SNR shells begun to emerge. The acceleration of $\sim$100 TeV electrons in SNRs was first suggested by the interpretation of non-thermal X-ray emission from objects such as SN 1006 as synchrotron radiation [55]. The first unambiguous evidence for the existence of $>$ TeV particles in supernova remnants come with the CANGAROO detection of RX J1713.7−3946 [56] and the subsequent higher angular resolution measurements with H.E.S.S. which resolved the shell in γ-rays [57]. The current challenges in the field are the expansion of the catalogue of TeV SNRs and the detailed study of the brightest objects, to identify the nature of the radiating particles (protons and nuclei or electrons).

The progress in this area since the last ICRC has been considerable. Three new TeV γ-ray sources associated with SNRs were presented together with further data on all the known γ-ray emitting SNRs. Those VHE SNRs with apparent shell-type morphology are shown in figure 3. RCW 86 is the weakest and most recently discovered of these objects [45]. Recent X-ray measurements suggest that RCW 86 is the remnant of the supernovae of 185 AD [58], placing it in the age range of the other TeV emitting SNRs. The 9.4σ H.E.S.S. detection shows evidence for a shell roughly matching the X-ray morphology of this object. Unfortunately, due to its lower flux, it will be very difficult to study this object in the same level of detail as RX J1713.7−3946 and RX J0852.0−4622.

The two other newly discovered SNRs: IC 443 and W 28, both appear to have emission correlated with available target material rather than with the radio/X-ray emission of the SNR shell itself, suggesting that the TeV emission may arise from interactions of hadronic CRs in (and surrounding) the SNRs. Both are also somewhat older than the shell-type TeV SNR of figure 3 (W 28: $\sim 10^5$ years, IC 443: $\sim 3\times 10^4$ years). The

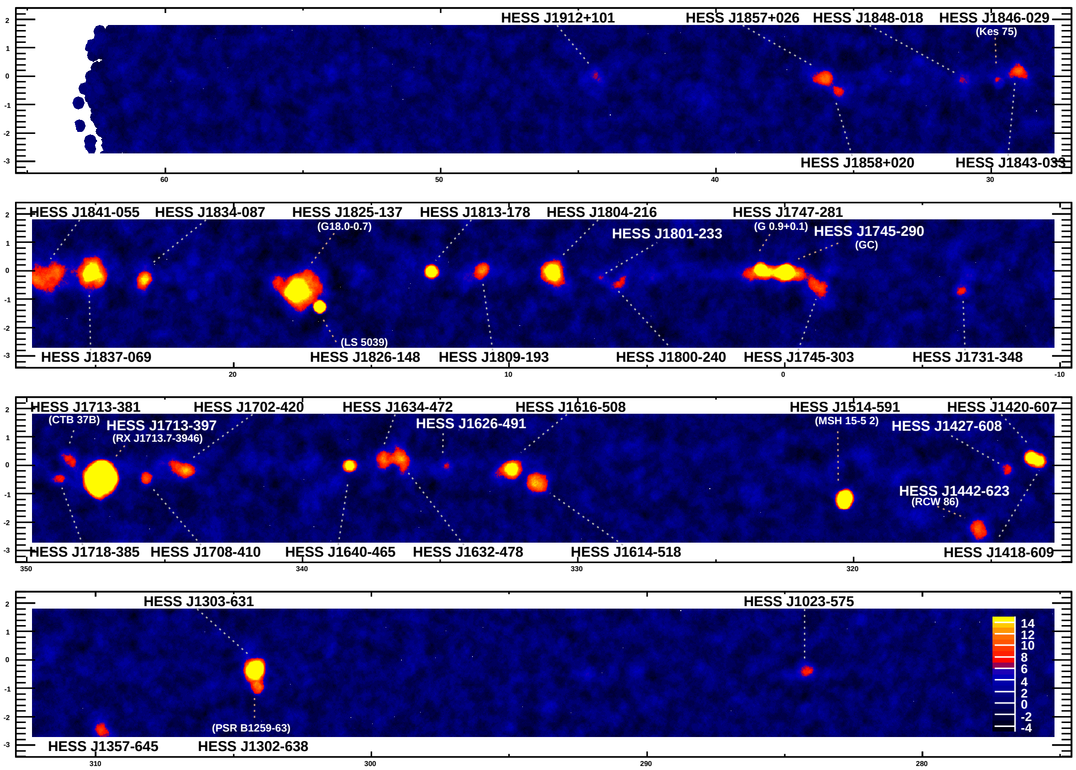

Fig. 2. The H.E.S.S. survey of the inner galaxy in $\sim$1 TeV γ-rays. The colour-scale indicates the statistical significance for somewhat extended sources. Image courtesy of the H.E.S.S. Collaboration.

H.E.S.S. data on W 28 indicate at least 3 separate peaks in the emission, one coincident with the brightest part of the radio shell (and the EGRET source 3EG J1800$-$2338), but with the others lying outside the shell, in coincidence with molecular clouds seen in ^{12}CO data [60]. TeV emission coincident with IC 443 was recently discovered independently by both the MAGIC [61] and VERITAS [62] collaborations. The γ-ray signal is at a significance of 5.7σ in 29 hours of MAGIC data, and 7.1σ in 16 hours of VERITAS observations. The centroid of the emission is consistent between the two measurements and is not coincident with the X-ray PWN within the remnant, nor with the SNR shell, but rather with a dense region towards the centre of the remnant (in projection). Maser emission tracing dense shocked gas is coincident with the emission, providing strong evidence that the signal arises in the interaction of CRs accelerated in the shell interacting with molecular material. There is no evidence so far for spatial extension of the signal, providing a motivation for deeper observations as morphology matching that of the molecular clouds would confirm this interpretation.

The two established TeV SNRs for which new γ-ray data were presented are RX J1713.7$-$3946 and Cassiopeia A. Three years of H.E.S.S. observations of the γ-ray bright SNR RX J1713.7$-$3946 have resulted in spectral and morphological data with very small statistical errors [44]. The energy spectrum of RX J1713.7$-$3946 now spans from 0.3 to 80 TeV with a very significant (4.8σ) signal above 30 TeV. This wide spectral coverage provides a much greater challenge to modellers then previous spectra, it now seems that inverse Compton scenarios for the emission are becoming unlikely, whilst a hadronic origin of the emission is favoured. The young and radio-bright SNR Cassiopeia A was first detected at TeV energies using the HEGRA telescope array [63] at the 5σ level in 232 hours of data spread over several years of

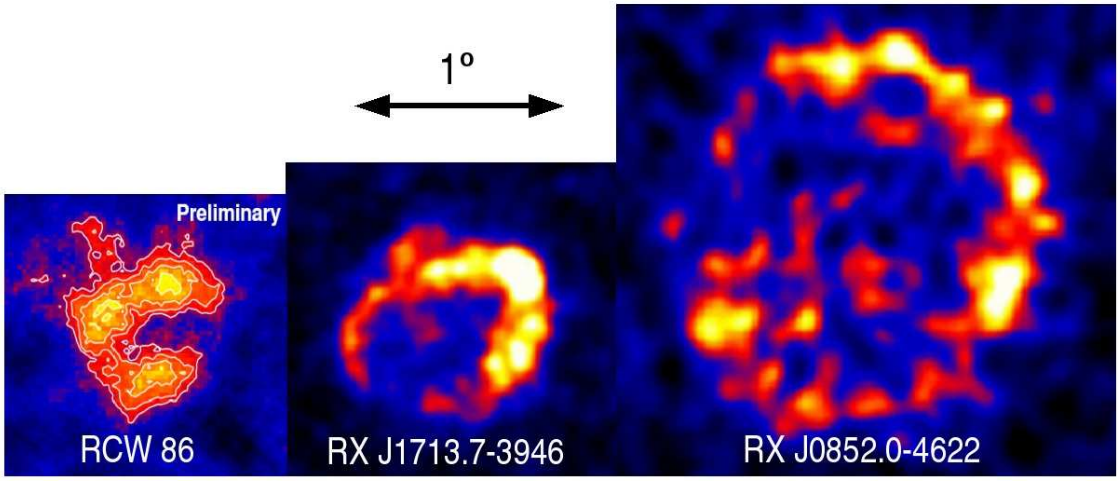

Fig. 3. The known shell-type γ-ray SNRs: RCW 86 [45], RX J1713.7−3946 [44] and RX J0852.0−4622 (*Vela Junior*) [59]. All images are smoothed and were obtained using H.E.S.S.

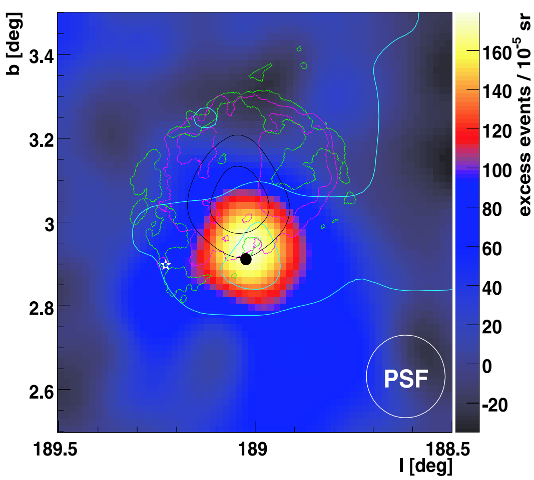

Fig. 4. γ-ray image of IC 443 as seen by MAGIC above 150 GeV (colour scale, reproduced from [61]). Overlayed contours show: ^{12}CO emission (cyan), 20 cm VLA data (green), X-ray emission as seen using ROSAT (purple) and confidence contours for the position of the EGRET source 3EG J0617+2238 (black). The star shows the position of the PWN CXOU J061705.3+222127. The black dot marks the position of a 1720 MHz OH maser. See [61] for details and references.

observations. This signal has now been confirmed using the MAGIC telescope [46], at the $5.2\,\sigma$ level using 47 hours of observations. The MAGIC photon index of 2.4 ± 0.2 is consistent with that measured using HEGRA: 2.5 ± 0.4. The radio size of Cas A ($4'$) means that VHE morphology of this object cannot be resolved with current instruments, but further spectral measurements with MAGIC (and VERITAS) may be very important.

The theory of particle acceleration in supernova shocks has been under continuous development for the last 30 years. The principal theoretical contributions in this area to this conference were those of Berezhko, Völk and Ksenofontov on the SNRs: Tycho [64], Kepler [65], SN 1987A [66], RX J1713.7−3946 [67] and Vela Junior [68]. In the cases where upper limits to the TeV emission exist (such as for Kepler's SNR) consistency with the non-linear model can be used to provide density and distance constraints. In those objects with measured TeV emission, the X-ray and γ-ray data appear consistent with the picture of shocks modified by hadronic CRs and γ-ray emission dominated by neutral pion decay. Further theoretical work involved more detailed treatment of hadronic interactions and the inclusion of nuclei in the calculation of γ-ray spectra [69]; the study of SNR evolution in a non-uniform medium [70]; and the possibility of 'Jitter' rather than synchrotron X-ray emission dominating in SNR [71].

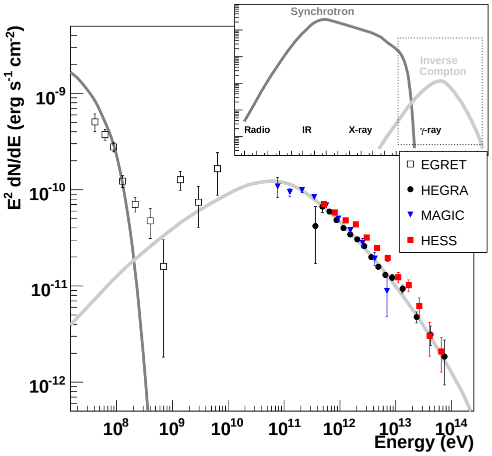

Fig. 5. The spectral energy distribution (SED) of the Crab Nebula. The inset shows a model radio-TeV SED with synchrotron and inverse Compton components from [73], the main panel shows the γ-ray part of the spectrum. EGRET and HEGRA data are reproduced from [73], H.E.S.S. [48] and MAGIC [47] data are those presented at this conference.

Pulsars and Pulsar Wind Nebulae

The Crab Nebula was the first TeV γ-ray source to be discovered [72] and is still the brightest steady and point-like source in the TeV sky. The γ-ray emission from the Crab is dominated by the pulsar below GeV energies and by steady emission from the Nebula above. Figure 5 shows the broad-band spectral energy distribution of the Crab Nebula, illustrating the double-peaked emission common to all pulsar wind nebulae (PWN). The two components are commonly attributed to synchrotron and inverse-Compton scattering of a population of ultra-relativistic electrons emerging from the termination shock of the pulsar wind.

The Crab Nebula is commonly used as a reference source in VHE γ-rays and to verify the sensitivity of instruments as predicted by Monte-Carlo simulations. Contributions from the VERITAS and MAGIC collaborations quote their sensitivities as $31\sigma/\sqrt{\mathrm{hour}}$ [74] (with 3/4 telescopes operational) and $19\sigma/\sqrt{\mathrm{hour}}$ [47], respectively. The newly commissioned ARGO YBJ detector [26], presented a 5σ on the Crab Nebula in 50 days, which compares favourably to the roughly $\sim 2\sigma/\sqrt{50\,\mathrm{days}}$ signal of MILAGRO (averaged over the full 7 year exposure). Seven years of Crab data from the Whipple 10 m telescope were also presented, illustrating the stability of this instrument [75]. Beyond its role as a calibration source, the Crab pulsar and its nebula are also of great interest astrophysically and several new spectral measurements of the Nebula were presented at this conference. The new H.E.S.S. measurements [48] extend the spectrum up to $\sim$80 TeV and at the low energy end, the MAGIC spectrum extends down to $\sim$80 GeV [47] (see figure 5). There is evidence for curvature in both data sets, with the MAGIC data being used to constrain the position of the high-energy peak in the spectral energy distribution to be 77 ± 47 GeV. The MILAGRO collaboration also presented a spectral measurement for the Crab Nebula, the first measurement of its kind for this instrument [76].

PWN have now emerged as the largest population of identified TeV sources (see table 2). As the number of extended VHE γ-ray sources along the Galactic Plane has increased the likelihood of chance associations with pulsars is now far from negligible. At this conference, the H.E.S.S. collaboration presented a systematic search for coincidences between sources detected in the H.E.S.S. galactic plane survey with radio pulsars [77]. As is evident from figure 6 there is a clear excess of γ-ray nebulae in positional coincidence with high spin-down luminosity pulsars (those with $\dot{E}/d^2$ above $\sim 10^{35}$ erg s^{-1} kpc^{-2}) over the expectations for chance coincidences. The implied efficiency in the conversion of spin-down power into TeV γ-ray production for these pulsars is around 1%.

Six new γ-ray sources coincident with high spin-down luminosity pulsars were presented here by the H.E.S.S. collaboration. These probable PWN can be roughly categorised by the characteristic spin-down age $\tau_{\mathrm{C}} \equiv P/2\dot{P}$ of the associated pulsar. Two of the associated pulsars are very young (i.e. similar to the Crab pulsar with τ_{C} $\sim$1000 years): PSR J1846$-$0258 in Kes 75 and G 21.5$-$0.9 [78]. The remaining four have $\tau_{\mathrm{C}} \sim 10^4$ years: HESS J1718$-$385,[79] HESS J1809$-$193 [80] HESS J1357$-$645 [17] and HESS J1912+102 [17], see [81] for a discussion of these objects.

Despite the large number of new PWN candidates, the most significant recent discovery in this

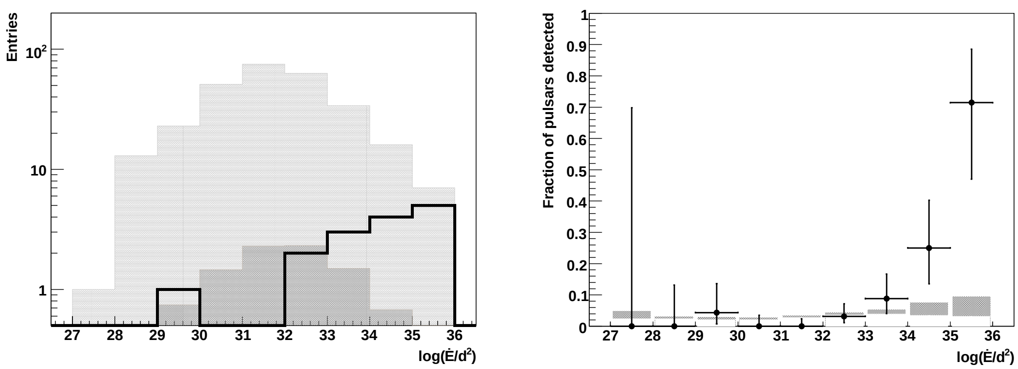

Fig. 6. The relationship of γ-ray nebulae to radio pulsars in the H.E.S.S. Galactic Plane Survey (reproduced from [77]). Left: number of radio pulsars where coincident γ-ray emission exists (thick histogram), as a function of the spin-down flux ($\dot{E}/d^2$) in erg s^{-1} kpc^{-2}. Thin lines show the whole population, and an estimate of the number of chance associations expected. Right: the fraction of radio pulsars which appear to have associated TeV γ-ray PWN, again as a function of spin-down flux. See [77] for details.

area is that of energy dependant morphology in HESS J1825$-$137 [52]. The new data from the H.E.S.S. collaboration show that the γ-ray emission 'shrinks' towards the pulsar PSR B1823$-$13 at high energies. Such behaviour has been seen before in X-ray synchrotron emission and has been interpreted as evidence for the cooling (energy-losses) of $>$ TeV electrons. The discovery of this effect in γ-rays provides us with a new tool with which to investigate the high energy particles in these objects.

A final PWN candidate worthy of note here is the *C3* 'hot-spot' detected using MILAGRO at the position of the Geminga pulsar [12]. Whilst the signal is estimated at only 2.8σ after correcting for statistical trials (and 5.1σ pre-trials) the coincidence with a powerful EGRET pulsar is compelling. The MILAGRO source has an apparent spatial extent of $\sim$2.8° $\pm$ 0.8°. Assuming this object lies at the Geminga distance of $\sim$300 pc, its intrinsic size is $\sim$15 pc, comparable to that of other more distant PWN such as MSH 15-52. Unfortunately, a source of this angular size will be extremely difficult to verify with current air-Cherenkov telescopes due to their restricted FoV.

No ground-based instrument has so far provided convincing evidence for pulsed γ-ray emission from a radio pulsar. The highest energy pulsed photons are those detected using EGRET at $\sim$10 GeV. As pulsed emission at higher energies is predicted in some scenarios, several groups have pursued pulsed emission searches from prominent GeV pulsars. Upper limits resulting from these searches were presented by the PACT [82], Tibet ASγ [83], H.E.S.S. [84] and STACEE [22] collaborations. Tantalising hints of a pulsed signal from the Crab were presented by the MAGIC collaboration. A 2.9 σ pulsed excess is seen in the phases of peak $>$100 MeV emission [47]. More data is clearly required to confirm this potentially very important result.

Binary Systems

Much controversy surrounds the early claims of TeV (and indeed PeV) emission from X-ray binary systems but recent progress has led to a catalogue of three well established γ-ray binaries. The first of these is PSR B1259$-$63 / SS 2883 a 3.4 year period binary of a pulsar in an eccentric orbit around a Be-star from which variable TeV emission was detected during its periastron passage in early 2004. The TeV emission from this object is thought to be associated with the pulsar wind and its interaction with the radiation field and material around the Be-star. The 2nd periastron to be observed by TeV instruments has just occurred (in July 2007) and will also be closely observed by several X-ray satellites. The H.E.S.S. collaboration presented a detection of this source in observations just before the conference, and plans for upcoming multi-wavelength observations [39]. The two remaining systems are both much closer binaries, for which the mass and indeed the nature of the compact object are unknown. The first of these to be discovered was LS 5039, detected in the H.E.S.S. galactic plane survey. The emission of LS 5039 is clearly periodic and it has been possible to extract a binary period of 3.9078 ± 0.0015 days (cf the optical period of 3.90603 ± 0.00017) from the γ-ray data alone [40]. Furthermore, the γ-ray spectrum of the object clearly varies as a function of phase, with a softening when the compact object lies behind its companion that may be indicative of γ-γ absorption or cascading. The second well established TeV emitting X-ray binary system is LS I +61 303, discovered by the MAGIC collaboration in 2006. This object has been the subject of subsequent observing campaigns with VERITAS [41, 42] and MAGIC [43] which were presented here. Whilst LS I +61 303 is certainly variable, it is not yet clear if it is strictly periodic, with good phase coverage hampered by an orbital period (26.5 days) close to that of the lunar cycle.

As the nature of the compact object is unknown in these two systems, it is not clear if the emission is due to a relativistic outflow from a neutron star (i.e. rotation powered as PSR B1259−63 / SS 2883 seems to be) or accretion on to a black hole or a neutron star which drives a relativistic jet. See [85] for a discussion. In this context, the recent evidence for TeV emission from the binary Cyg X-1, which contains a $>13M_{\odot}$ black hole, is very exciting: such a system must be powered by accretion rather than rotational energy. A 4.9σ excess is seen in one 79 minute period in the 40 hours of MAGIC observations [86]. The apparent TeV outburst occurred during a period of enhanced X-ray activity, but there does not appear to be a correlation between X-rays and γ-rays on short timescales. The estimated post-trials significance of this signal is 4.1σ, but as was discussed at the conference, the assessment of statistical trials is not straightforward in this case. For this reason, the status of Cyg X-1 as a TeV emitter cannot yet be considered as proven beyond doubt (hence its omission from table 2). A confirmation of this signal using VERITAS or via further MAGIC observations is therefore highly desirable.

The Galactic Centre

The central ∼100 pc of our galaxy is host to a wide range of potential TeV emitting objects. The most exotic of these, and also the most widely discussed, are the supermassive black hole Sgr A* and a hypothetic cusp of self-annihilating dark matter. TeV emission from close to Sgr A was discovered independently using the Whipple [87], CANGAROO [88] and H.E.S.S. [89] instruments in 2004. In addition to this point-like source (HESS J1745−290), diffuse emission correlated with the giant molecular clouds (GMCs) of the central region was discovered using H.E.S.S. in 2006 [90]. The theoretical work on the γ-ray emission of the galactic centre (GC) region at this conference was focused primarily on the diffuse emission. Moskalenko et al discussed CRs injected from the supernova remnant Sgr A East, propagating through and radiating in the GMCs of the GC[91]. Erlykin and Wolfendale considered an origin of the emission as a consequence of a succession of SNRs in the region over the past 10^5 years [92].

Whilst no new experimental results on the diffuse component were presented, there were four contributions on the central source HESS J1745−290. Over the past 2–3 years there has been a major effort to drive down the systematic errors on pointing of the H.E.S.S. telescopes, resulting in an extremely precise localisation of the TeV emission at the GC [93], the reported centriod of the emission has $6''$ statistical and $6''$ systematic errors. The new position effectively excludes the SNR Sgr A East as the dominant source of the TeV emission. The PWN candidate G 359.95−0.04 and the supermassive black hole remain as the most likely candidates.

The observation of a major X-ray flare from Sgr A* during simultaneous measurements with H.E.S.S. and Chandra in July 2005 [94] provides a unique opportunity to test the association of the TeV source with the supermassive black hole. There was no evidence for an increase in the γ-ray flux during this event, constraining any flaring TeV component to be less than 100% of the steady component during the ≈30 minutes of the flare. A search of the full H.E.S.S. data set yielded only upper limits on variability and QPOs [95]. These results limit models for HESS J1745−290 as arising from acceleration at Sgr A* to those in which the accelerated particles propagate rather far ($\sim$1 pc) from the supermassive black hole before losing significant energy (see for example [96]). Limits on a dark matter annihilation component to the spectrum of HESS J1745−290 were also presented [97].

Unidentified Sources

The majority of galactic TeV γ-ray sources have no clear counterpart at other wavelengths. This situation likely results from a combination of experimental and physical considerations. A primary reason is certainly that many of these sources are widely extended and may have morphology that differs significantly from that at other wavelengths. There are two basic categories of unidentified TeV source: 1) sources where there is a candidate for the emission, but no strong evidence to support an association (for example in several cases there is an ambiguity between SNR shell emission and PWN emission due to a lack of angular resolution and/or statistics) and 2) sources where *no* good candidate exists at sub-γ-ray wavelengths (TeV sources with GeV associations cannot be considered as identified) which have sometimes been referred to as 'dark sources'. The first example of the latter type was TeV J2032+4130, discovered by the HEGRA collaboration in 2002 and has now been confirmed using MAGIC [98]. The second such object was HESS J1303−631 , serendipitously discovered using H.E.S.S. in 2004 and recently confirmed using CANGAROO-III [19]. Many more objects in this class have followed. A summary of sources with no good counterpart at any wavelength below the γ-ray was presented here by the H.E.S.S. collaboration [99], including six TeV sources newly discovered in the H.E.S.S. galactic plane survey. A further unidentified H.E.S.S. source: HESS J0632+057, was recently discovered close to the Monoceros Loop SNR and is unusual in its point-like nature [100].

Very recently the MILAGRO collaboration has added three more objects to this list: MGRO J2031+41, MGRO J2019+37 and MGRO J1908+06 [12]. These objects have fluxes approaching that of the Crab Nebula above 20 TeV and one (MGRO J2031+41) is significantly extended beyond the $\sim 1^\circ$ angular resolution of MILAGRO. Flux upper limits on *point-like* emission from MGRO J2019+37 from the VERITAS [101] and MAGIC [102] collaborations were presented which exclude extrapolation of the MILAGRO fluxes down to $\sim$1 TeV with typical $E^{-2.3}$ type spectra. However, as this source is probably extended (best fit diameter $1.1 \pm 0.5^\circ$) these point source ($<0.1^\circ$) limits may not be meaningful. Indeed, MGRO J2019+37 has now been confirmed using Tibet ASγ [103], an instrument with comparable resolution to MILAGRO. The detection of MGRO J1908+06 by the H.E.S.S. collaboration presented here [104] is the first confirmation of a source detected by a non-IACT instrument by an IACT system. The excellent agreement on the $\sim$20 TeV flux of this source, illustrated in figure 7, provides further confidence in the MILAGRO detections. Figure 7 also illustrates the power of the imaging technique for spectral measurements. The H.E.S.S. data shown were obtained in just a few hours, in comparison to the 7 years integration of the single MILAGRO point on this $\sim 0.5^\circ$ diameter source. Nevertheless, wide field of view instruments such as MILAGRO are certainly complementary to the existing narrow FoV IACTs for the detection of extended emission and such high duty cycle instruments have a clear advantage in the search for transient phenomena.

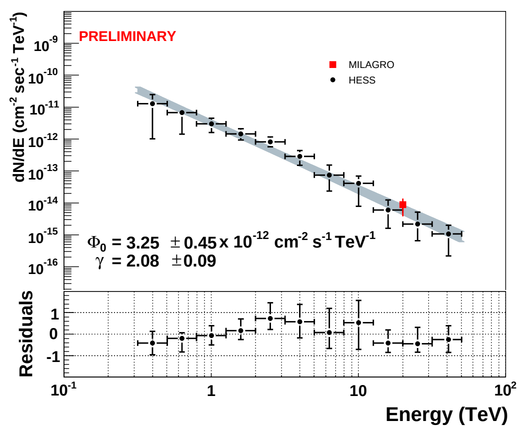

Fig. 7. Energy spectrum for MGRO J1908+06 from MILAGRO and H.E.S.S. data. The lower panel shows residuals to a power-law fit. Reproduced from [104]

One exotic explanation that has been put forward for these unidentified sources is that they originate in the annihilation of dark matter in localised 'clumps'. A major difficulty of this explanation is the energy spectrum of the sources, for example HESS J1303−631 [105]. The more prosaic explanation put forward is that they originate in the collisions of cosmic-ray hadrons, with little emission at other wavelengths (in contrast to electrons which typically produce comparable fluxes in synchrotron emission). However, in this scenario the acceleration site for these CRs remains a mystery.

Perhaps the most significant of the new sources without a clear counterpart is HESS J1023−575 [106]. This object is coincident with the massive stellar cluster Westerlund 2 the second most massive young cluster in our galaxy. Whilst this association may be coincidental, the colliding winds of stars in this cluster can certainly provide the energy required to produce the γ-ray emission and acceleration in such objects seems plausible (see for example [107] and references therein). As such, HESS J1023−575 may well be the first of a new class of galactic γ-ray sources. As well as the conventional γ-ray production mechanisms discussed above, it was suggested at the conference that the photo-disintegration of nuclei may play an important role in this object and in other high radiation-field environments [108].

OG 2.3: Extragalactic Sources

AGN

Active galactic nuclei (AGN) are thought to harbour actively accreting supermassive black holes which drive relativistic jets into their environments. The *blazar* subclass of AGN is characterised by rapid variability and high energy (>0.1 GeV) emission. These objects are thought to represent AGN with jets aligned very closely (<10°) with the line of sight to the observer, resulting in greatly enhanced fluxes through beaming effects. Blazars were the dominant source class detected with EGRET at GeV energies and beginning in 1992 with Mrk 421, a class of higher energy peaked *TeV blazars* has been established. The spectral energy distribution of blazars is double peaked with a minimum typically somewhere in the hard X-ray to soft γ-ray energies (∼1 MeV). The most common explanation for the two components is as synchrotron and inverse Compton radiation of a population of energetic electrons within a region with bulk relativistic motion along the jet. The high energy component has also been interpreted as due to accelerated hadrons (via several different radiation processes). These explanations are of particular relevance to the cosmic ray field as AGN are one of the primary candidates for the acceleration of the ultra-high energy cosmic rays (those with $E > 10^{19}$ eV).

The theoretical work on AGN at this conference included studies of time variability in inverse Compton γ-ray spectra [109] and on the effects of jet expansion on blazar emission properties [110]. The vast majority of contributions were, however, experimental in nature. There were two main experimental highlights: the discovery of seven new TeV blazars and the measurement of extreme γ-ray variability in three previously known objects.

Table 3 summarises the known TeV AGN, including the seven new objects presented at this conference. There are now sufficient numbers of these objects to allow population studies, a project which is now underway. At this conference a study was presented exploring the relationship of the TeV emission to the properties of the active galaxy, including the black hole mass [111]. The sources of table 3 are ordered by redshift, illustrating the recent progress made in measurements of more distant objects. Aside from their interest as particle accelerators, the TeV blazars are important beyond the field of high energy astrophysics as they have been used place constraints on the star-formation history of the universe. The energy-dependent absorption of γ-rays via pair-production on the extragalactic background light (EBL) can be used to derive limits on the energy density of this photon field and hence on the integrated radiation history of galaxies. Conversely this absorption places an energy dependent horizon on γ-ray observations. An optical depth of $\tau = 1$ is reached at a redshift of ∼0.1 for 1 TeV γ-rays. Only relatively recently have experiments with substantial sensitivity in the 0.05–1 TeV range existed, leading to a rapid expansion in the number of $z > 0.1$ TeV blazars.

Three of the these new objects were discovered using the H.E.S.S. instrument: PKS 0548-322, 1ES 0229+200 and 1ES 0347−121. These objects are all classified as high energy peaked BL

Lac objects or HBLs, based on the position of the peak in the synchrotron spectrum. The relatively hard energy spectra measured for 1ES 0229+200 and 1ES 0347−121 (photon indices ∼2.5 and ∼3.1 respectively) make them particularly useful for constraining the EBL. Under the assumption that the intrinsic spectrum of these objects has a photon index not less than 1.5 (that expected for inverse Compton radiation of an E^{-2} electron spectrum radiating in the Thompson limit), limits on the mid- and near Infra Red were presented that approach the lower limits from galaxy counts at these wavelengths [112]. Combined EBL limits using all previously known TeV blazars were also presented here [113].

The four new objects presented by the MAGIC collaboration are all interesting for three rather different reasons. Firstly, the detection of BL Lacertae is important is this is the first low energy peaked BL Lac object (LBL) to be detected using a ground-based instrument [124]. It seems likely that a large number of such sources may be detected by lower threshold instruments such as HESS-II and MAGIC-II. The MAGIC discoveries of VHE emission from both Mrk 180 and 1ES 1011+496 arose from observations triggered by optical activity [122]. The implied optical/TeV connection may be important not just for our understanding of these objects but on the practical grounds that optical monitoring of a large sample of AGN is much easier to achieve than a X-ray campaign on a similar scale. 1ES 1011+496 ($z = 0.212$) was also (briefly) the most distant known TeV source with a well established redshift, displaced by the MAGIC discovery of γ-ray emission from 3C 279 [136] first announced at this conference. The discovery of TeV emission from the GeV bright blazar 3C 279 is important in two respects: firstly as it marks a major step forward in redshift for ground-based instruments (to $z = 0.536$) and secondly as this object belongs to a rather different class of AGN: the Flat Spectrum Radio Quasars. 3C 279 was the brightest extragalactic object detected using EGRET and is hence certainly a GeV rather than a TeV blazar. With the upcoming launch of GLAST, 3C 279 may become the only object for which simultaneous GeV and TeV measurements are possible on ∼1 hour timescales. The MAGIC signal from 3C 279 (shown in figure 8) consists of one night of significant emission from a ten night observation. The signal is at the 6.1σ level (without accounting for statistical trials) in an energy band from 80–220 GeV, and at the 5.1σ above 220 GeV. The signal in the higher energy band is particularly surprising given the redshift of this object. The energy spectrum of this source will be extremely interesting from the perspective of EBL absorption. Given the importance of this detection, caution is necessary and a very careful assessment of statistical trials (notoriously difficult for variable sources) and systematic effects is clearly needed. However, given the strength of the signal, and its independent confirmation in a second energy band, it seems highly likely that 3C 279 is a VHE γ-ray source. As 3C 279 is readily accessible from both hemispheres a confirmation should be possible rather quickly and this object should be a prime candidate for coordinated monitoring with MAGIC, VERITAS and H.E.S.S.

Since the 29th ICRC spectacular flaring activity has been seen in two TeV blazars: Mrk 501 [120] and PKS 2155−304 [128]. The Mrk 501 activity observed using MAGIC in July 2005 was the first major outburst observed by a instrument of the more sensitive new generation. As such the temporal and spectral resolution possible surpassed that of previous measurements. The highlight of these observations is the detection of very fast (∼2 minute flux doubling time) variability with a significant lag between photons of different energies (see figure 9). Such lags are a potentially powerful diagnostic of acceleration and energy loss processes and the short timescales involved place tight limits on the size of the emitting region and the Doppler factor of the jet ($\delta > 16$ is inferred from these measurements [120]).

The activity of PKS 2155−304 observed using H.E.S.S. in July 2006 was even more dramatic [128]. Figure 10 shows the light curve of the night with the highest flux, in which the emission reached fluxes more than two orders of magnitude higher than the quiescent flux of this object. Short timescale variability is clearly evident in figure 10 and the best measured individual flare is the first of the night with a best fit rise-time of 173 ± 23 seconds. No evidence for energy dependent time-lags was presented at the conference.

Object	Discovered	Year	z	Class	Contrib.
M 87	HEGRA	2003	0.004	LINER	[114, 115, 116]
Mrk 421	Whipple	1992	0.031	HBL	[117, 118, 119]
Mrk 501	Whipple	1996	0.034	HBL	[120, 119, 20]
1ES 2344+514	Whipple	1998	0.044	HBL	[121]
Mrk 180	MAGIC	2006	0.046	HBL	[122]
1ES 1959+650	TA	2002	0.047	HBL	[123]
BL Lac	MAGIC	2006	0.069	LBL	[124]
PKS 0548−322	HESS	2006	0.069	HBL	[125]
PKS 2005−489	HESS	2005	0.071	HBL	[126]
PKS 2155−304	Durham	1999	0.116	HBL	[127, 128, 129, 130]
H 1426+428	Whipple	2002	0.129	HBL	[131]
1ES 0229+200	HESS	2007	0.140	HBL	[112]
H 2356−309	HESS	2005	0.165	HBL	[126]
1ES 1218+304	MAGIC	2005	0.182	HBL	[132, 109]
1ES 1101−232	HESS	2005	0.186	HBL	[133]
1ES 0347−121	HESS	2007	0.188	HBL	[112]
1ES 1011+496	MAGIC	2007	0.212	HBL	[122]
PG 1553+113	HESS	2005	>0.25	HBL	[134, 135]
3C 279	MAGIC	2007	0.536	FSRQ	[136]

Table 3. The known very high energy γ-ray emitting AGN. The instrument used for the first VHE detection is given together with the year of discovery, the redshift and the object class. The main contributions to this conference containing VHE data are listed for each object.

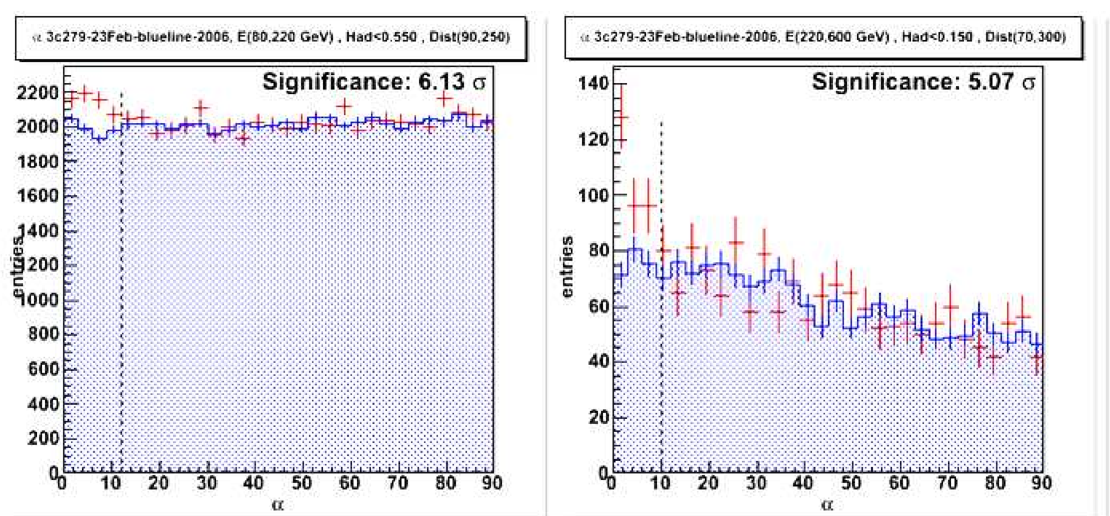

Fig. 8. VHE emission from 3C 279 on the 23rd of February 2006. *Alpha-plots* for *on-* (points) and *off-* (histograms) data collected using the MAGIC telescope in two energy bands: left: 90-220 GeV and right: 220-600 GeV. α is the angular distance between the major axis of a Cherenkov image seen in the camera and the line connecting the image centriod to the position of the target source.

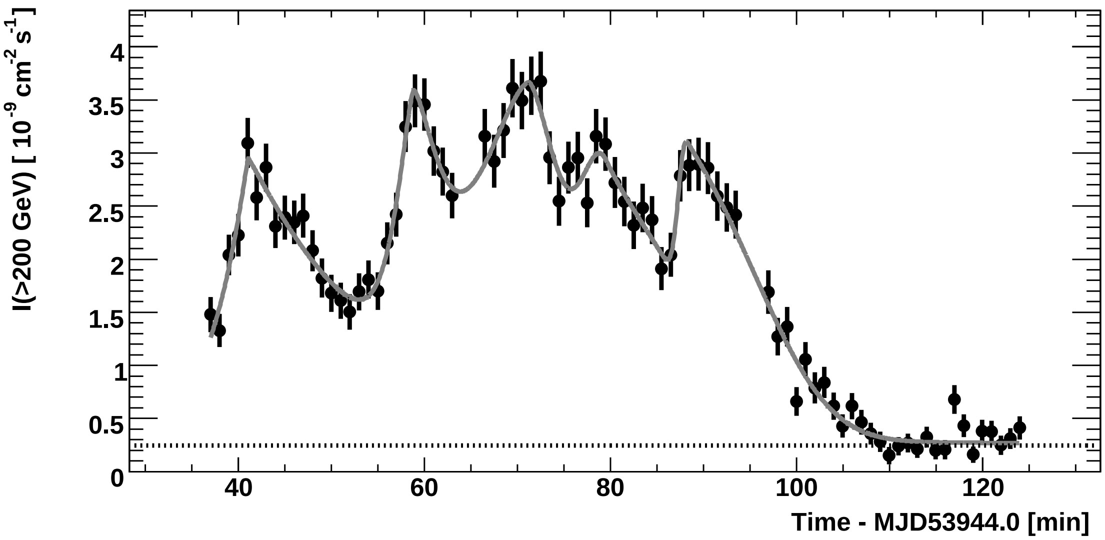

Fig. 10. H.E.S.S. VHE flux light-curve from a flare of PKS 2155−304 on the $28^{\rm th}$ of July 2006. The one-minute binned data are fit to a multi-component Gaussian (smooth curve). The flux of the Crab Nebula is indicated as a dashed line for comparison. Reproduced from [128].

A possible 'spin-off' of these measurements of fast variability in distant objects is to constrain any energy-dependence of the speed of light and hence probe the energy scale of Quantum Gravity effects. See [137] for details.

The only non-blazar known to emit TeV photons is the nearby ($z = 0.004$) radio galaxy M 87, the core of which harbours the most massive known black hole in the nearby universe. The angle between the line-of-sight and the jet axis appears to be $\sim$30° in this system, in contrast to the $<$10° inclination angles of the blazars. Given the reduced beaming effects in such a system and the mass of the black hole, the two day timescale variability discovered using H.E.S.S. [114] is particularly surprising. Causality arguments have been used to derive a limit of $5\delta R_s$ on the size of the emission region, where δ is the Doppler factor of the source and R_s is the Schwarzschild radius of the supermassive black hole. Figure 11 shows the light-curve of M 87 on long (year) and short (day) timescales including data from several VHE instruments. The most recent data shown are the 5.1σ detection of this source using VERITAS earlier this year [116].

Potential Extragalactic TeV Source Classes

Although AGN are the only extragalactic TeV source class identified so far, there are several other object classes with TeV fluxes which may be reachable with current or near future instruments. The primary target class in terms of investment of observing time seems to be Starburst Galaxies and their cousins the ultra-luminous infra-red galaxies or ULIRGs. These objects present the possibility of exploring CR acceleration associated with stellar life-cycles (normally assumed to occur in SNRs) in an integrated fashion. Upper limits on the Starbursts in nearby galaxies NGC 253 and M 83 were presented by the H.E.S.S. collaboration [138], and on the ULIRG Arp 220 using MAGIC [139]. These limits are already deep enough to challenge the simplest scenarios for cosmic acceleration and propagation in these objects and further observations remain well motivated.

As the largest gravitationally bound structures in the universe, Galaxy clusters are of crucial importance in many areas of astrophysics and cosmology. As the escape and energy-loss timescales of ultra-relativistic hadrons in these systems is longer than a Hubble time [140] γ-ray observations of clusters could potentially probe the in-

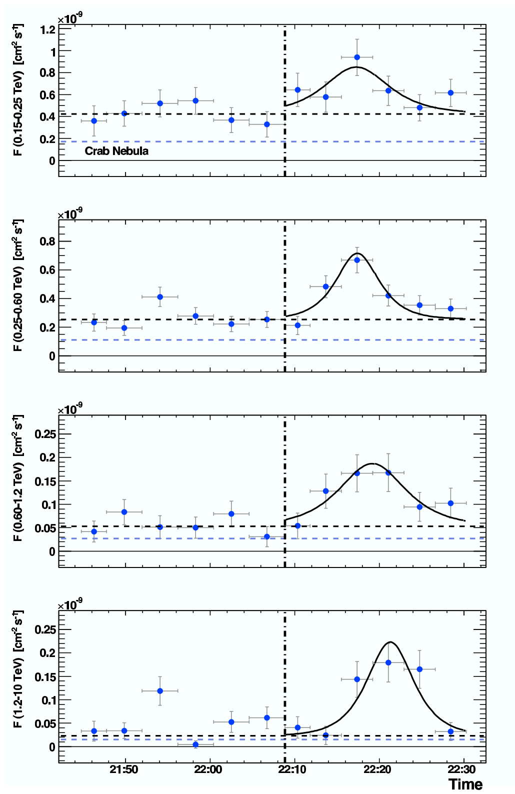

Fig. 9. MAGIC light-curves of a flare from Mrk 501 on the 9$^{\text{th}}$ of July 2005. The data are subdivided in to 4 energy bands. The flux of the Crab Nebula in each band is indicated by a dashed horizontal line. Reproduced from [120].

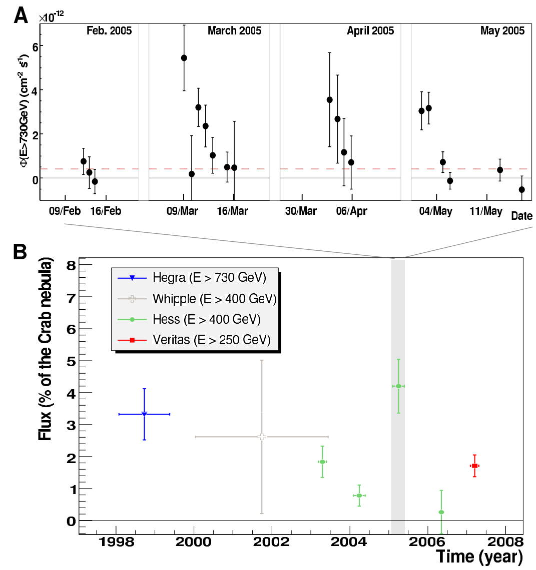

Fig. 11. Long and short-term variability in the TeV emission of M 87. A) Short-term variability seen in the light-curve of M 87 using H.E.S.S. in 2005, reproduced from [114] and B) Long-term variability as seen using HEGRA, Whipple, H.E.S.S. and VERITAS, reproduced from [116].

tegrated CR acceleration history of these objects. Possible sites of injection of CRs into the intracluster medium include shocks associated with large scale structure formation (merger and/or accretion shocks), stellar processes within cluster member galaxies (e.g. SNR) and AGN outbursts [141]. Flux upper limits from the H.E.S.S. and CANGAROO-III instruments were presented on the galaxy clusters Abell 496 and Coma [142] and on Abell 4038 and Abell 3667 [143].

The increasingly deep upper limits on the most prominent members of these source classes suggest that non-beamed emission from extragalactic sources may be difficult for current TeV instruments to detect. Nevertheless, it seems likely that these source classes lie within the reach of near future instruments such as GLAST and the second phase instruments of H.E.S.S. and MAGIC, and could have a huge impact on the cosmic ray field.

Other extragalactic objects considered include globular clusters [144] and possible dark matter annihilation in dwarf galaxies [25].

OG 2.4: Gamma-Ray Bursts

Gamma-ray bursts (GRBS) are widely understood as originating in relativistic ‘fireballs’ following the core-collapse of massive stars and/or the coalescence of two compact objects. A high energy component (possible from inverse Compton scattering of high energy electrons) may exist in these bursts and emission up to $\sim$ 20 GeV was seen using EGRET, but as of yet no completely convincing case for TeV emission from a GRB exists. Some theoretical work on GRBs was presented at this conference [145, 146, 147, 148] but the majority of the contributions were experimental in nature and most of these presented fluence limits on individual GRBs in the TeV energy range.

The Gamma-ray bursts Coordinates Network (GCN) provides automatic alerts to subscribing ground-based instruments following the detection of a GRB by a satellite based detector. Currently, most such alerts are triggered by the Swift satellite but HETE-2 and Integral also provide alerts. Most TeV instruments subscribe to this system and respond to alerts where possible. The response time of Cherenkov telescopes is limited in principle only by the typical GCN delay of a few seconds plus the slewing time of the telescope(s). The MAGIC telescope was designed in a light-weight manor with the specific aim of slewing rapidly to GRBs and has a speed of $\sim$5°/s. The more heavily built H.E.S.S. and VERITAS telescopes slew at $\sim$2°/s and $\sim$1°/s respectively. Four pointing instruments presented upper limits from their GRB programs: MAGIC [149], H.E.S.S. [150], VERITAS [151] and STACEE [23]. H.E.S.S. is unique in having observed a burst with zero delay: GRB 060602B occurred serendipitously at 2.5° from the pointing direction of the array [152]. However, this burst has may in fact have been an X-ray flash of galactic origin. After this, the fastest response of a pointed instrument to a GRB is the MAGIC of GRB 050713a, starting 40 seconds after the burst trigger, but in the absence of a redshift measurement the fluence upper limit obtained is hard to interpret.

Very wide field instruments such as MILAGRO and Tibet ASγ have clear advantages in the search for TeV emission from GRBs. Their close to 100% duty cycle and very large field of view ensure that prompt VHE emission from many bursts can be tested. The disadvantage of somewhat poorer fluence sensitivity for this instruments is probably outweighed by the advantage of a zero response time, but this obviously depends on the (unknown) time profile of the high energy component of the burst. The MILAGRO collaboration presented upper limits from two approaches probing different energy bands [153, 154].

All VHE instruments face a severe difficulty in the limited redshift range to which they are sensitive due to EBL absorption. Only a small fraction of GRBs occur at small enough distances and only a fraction of these will have measured redshifts. It may therefore require considerable patience to measure > 100 GeV emission from GRBs even if this component exists. An instrument such as HAWC, with the advantages of MILAGRO, but with a lower energy threshold providing much greater redshift coverage, could be well suited to such studies [155]

Summary

It is clear that γ-ray astronomy is making rapid progress towards answering some of the important questions in cosmic ray physics and contributing to several topics well outside the cosmic ray field. It is already clear that GLAST will, if successfully deployed, have an enormous impact on the field, and it is highly likely that these results will dominate the next ICRC. For the moment the highlights are the results at $\sim$TeV energies. Figure 12 shows the catalogue of known VHE γ-ray sources as of mid-2007. The number of sources is very likely to grow from the current $\approx$71 to cross the 100 source threshold before the next ICRC. More importantly the number of established source *classes* has grown, and there are hints of new source types which may be established rather soon. The precision with which the brightest sources are being measured, for example all $6''$ errors on the centroid of the emission from the Galactic Centre, and the resolved energy dependent morphology in HESS 1825$-$137, are perhaps the best illustration of the progress made in the field. Also extremely important is the detection of 3C 279 using MAGIC, marking a dramatic increase in the volume of the universe accessible to ground-based γ-ray detectors. With the completion of a major new VHE instrument, VERITAS, and the ongoing construction of H.E.S.S.-II and MAGIC-II, it is likely that this rapid progress will continue for some time to come.

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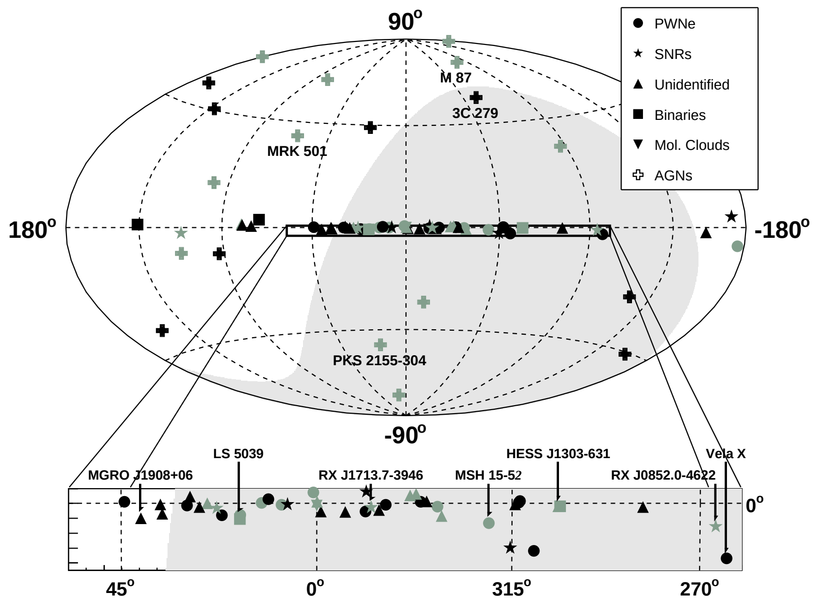

Fig. 12. The catalogue of known TeV sources as of the 30th ICRC. The positions of known TeV emitters are shown in galactic coordinates. Darker symbols indicate discoveries since the 29th ICRC in 2005. The shaded region indicates the part of the sky more readily accessible from the southern hemisphere (Declination $>0°$), adapted from [32].

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