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INVITED REVIEWS

TeV gamma-ray astronomy

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Abstract The field of ground-based gamma-ray astronomy has enjoyed rapid growth in recent years. As an increasing number of sources are detected at TeV energies, the field has matured and become a viable branch of modern astronomy. Lying at the uppermost end of the electromagnetic rainbow, TeV photons are always preciously few in number but carry essential information about the particle acceleration and radiative processes involved in extreme astronomical settings. Together with observations at longer wavelengths, TeV gamma-ray observations have drastically improved our view of the universe. In this review, we briefly describe recent progress in the field. We will conclude by providing a personal perspective on the future of the field, in particular, on the significant roles that China could play in advancing this young but exciting field.

Key words: gamma-rays: observations

1 INTRODUCTION

When one thinks of high energy astronomy, satellites tend to come to mind right away, because the atmosphere of the Earth is entirely opaque to radiation at UV, X-ray, or gamma-ray wavelengths (which is a good thing for human vitality). In order to directly detect such radiation, which comes from a celestial object, one must therefore place the detector above the atmosphere. Although sounding rockets and balloons played a critical role in the early days of high energy astronomy, satellites were the ultimate vehicle to launch the field into prominence. Over the past several decades, numerous breakthroughs in the field have been enabled by space-borne observatories.

However, satellite-based experiments become increasingly ineffective in detecting gamma-rays at increasing energies. When photons reach an energy of tens of GeV, it is, in fact, problematic to detect them directly, because of the practical difficulty in constructing a suitable detector to “stop” them. This is where ground-based gamma-ray experiments come in and contribute. At such high energies, there is a unique window of opportunity to do high energy astronomy on the ground. Although the gamma-rays cannot penetrate the atmosphere all the way down to the ground, the consequences of their interactions with the atmosphere can be observed and quantified to infer their spatial, spectral, and temporal properties. In essence, one uses the atmosphere as part of a giant gas detector to register gamma-ray radiation.

1.1 Experimental Principles

The interactions between GeV–TeV photons and particles in the atmosphere predominantly result in relativistic electron–positron pairs, as illustrated in Figure 1. These secondary electrons or positrons lose energy mainly by bremsstrahlung radiation to produce gamma-rays. The latter may produce more pairs and the pairs produce more gamma-rays ... on and on the cascading process continues, until ionization becomes the main channel of energy loss for relatively low-energy electrons and positrons. Therefore, upon the incident of each gamma-ray on the atmosphere, a shower of charged particles is formed in the atmosphere. Moving downward, the density of shower particles increases until it reaches a maximum (known as the shower maximum), typically at an altitude of roughly 10 km above sea level, and then begins to decrease. The air showers may be observed through the detection of light emitted (or induced) by the shower particles or the detection of those shower particles that manage to reach the ground.

Unfortunately, not all air showers seen are initiated by gamma-rays. In fact, only a tiny fraction of them are. This is because the showers are also formed when cosmic ray particles (mainly protons) interact with the atmosphere, as also illustrated in Figure 1. Since cosmic rays outnumber cosmic TeV gamma-rays by many orders of magnitude, picking out gamma-ray-induced showers is truly like finding a needle in a haystack! This is a main reason why it took about two decades of painstaking development before the first TeV gamma-ray source, the Crab Nebula, was convincingly detected (Weekes et al. 1989). The key for the success lies in the formulation of an empirical procedure to separate the showers initiated by gamma-rays from those by cosmic rays. There are physical differences between electromagnetic showers and hadronic showers. Unlike electromagnetic interactions, hadronic interactions mainly result in pions. Therefore, hadronic showers mainly contain the decaying product of pions, including muons, electrons, positrons, and neutrinos from charged pions ($\pi^{\pm}$), as well as gamma-rays from neutral pions (π^0). While subsequent π^0-induced events are indistinguishable from the gamma-ray events of interest, $\pi^{\pm}$-induced events manifest themselves, e.g., in the associated muons or neutrinos. It should be noted that the background events induced by cosmic ray electrons are also electromagnetic in origin and are thus difficult to eliminate.

Two broad classes of experiments are designed to explore the differences between electromagnetic and hadronic showers. One is based on detecting shower particles (photons, muons, electrons, positrons, and neutrinos) that reach the ground, while the other is based on detecting Cherenkov radiation induced by superluminal charged particles in air showers. The main advantages of the former include a long duty cycle and a large field-of-view, while those of the latter include high sensitivity (due to efficient gamma–hadron separation), low energy threshold, and good energy and spatial resolution. To a large extent, therefore, the two types of experiments are complementary in practice (e.g., wide-field surveying vs narrow-field imaging). The examples of particle-based experiments include Milagro (which is no longer in operation) and ASγ and ARGO, both of which are located at the Yangbajing (YBJ) International Cosmic Ray Observatory in Tibet, China and are ongoing. Cherenkov experiments can be further divided into imaging experiments, such as CANGAROO-III, HESS, MAGIC, and VERITAS, and non-imaging experiments, such as CELESTE and STACEE. The imaging technique was pioneered by the Whipple Collaboration, which led to the detection of the very first TeV gamma-ray source, and was greatly enhanced by the HEGRA Collaboration through stereoscopic imaging with multiple telescopes. The stereo-imaging technique is employed in the current (and future) generation of narrow-field imaging experiments. In general, the imaging experiments are far more sensitive than their non-imaging counterparts. The duty cycle of Cherenkov experiments is limited by the requirement of their operating under good weather on moonless nights. For example, VERITAS typically runs for 700–800 h in a year, or a duty cycle of $< 10\%$, compared to the $>90\%$ duty cycle of, e.g., Milagro. More technical details can be found in a recent review article by Aharonian et al. (2008).

1.2 Development and Scientific Drivers

The primary driver for the development of TeV gamma-ray astronomy is to utilize the unique window of opportunity on the ground to push astronomy towards the uppermost end of the electromagnetic spectrum. As the history of astronomy has shown, a new window into the universe nearly always brings about new discoveries. The prospect of probing the most energetic and most violent phenomena in the universe provided strong motivation for decades of painstaking efforts to develop and perfect techniques for the field.

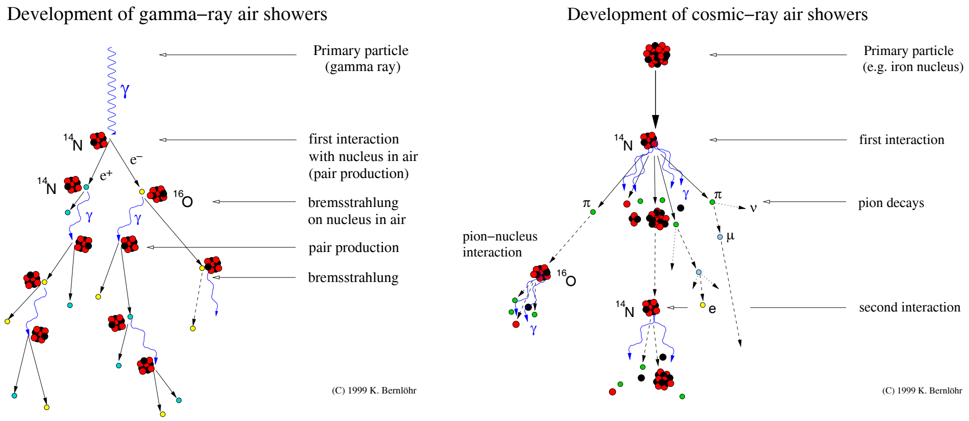

Fig. 1 Schematic of air shower development. Note the presence of muons (and neutrinos) associated with hadronic showers. Reproduced with permission from Konrad Bernlöhr.

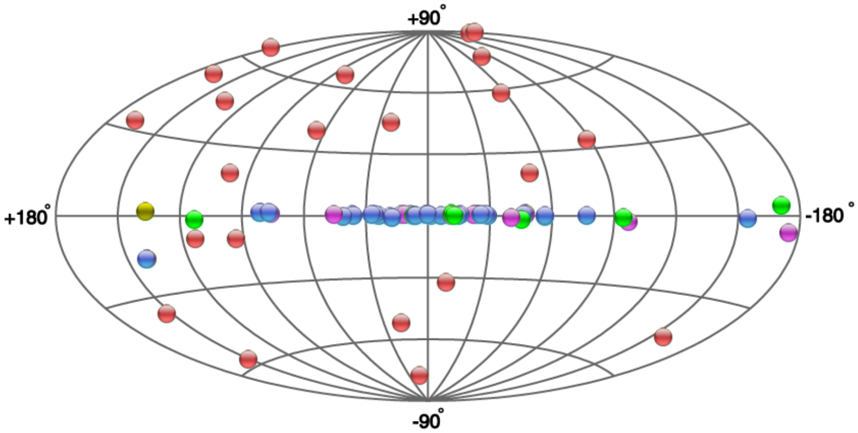

Fig. 2 Distribution of discrete TeV gamma-ray sources (as of March 2009). The sky map is in galactic coordinates. The colors differentiate various classes of sources (for legend see *http://tevcat.uchicago.edu*). Courtesy of the TeVCat Team.

TeV gamma-ray astronomy attempts to address many of the same questions that other branches of astronomy do. They include: cosmic sources of TeV photons, radiation geometries and mechanisms, properties of radiating particles and their environments, and so on. The field also offers an excellent example of interdisciplinary, collaborative efforts between astronomers and physicists, because it also explores topics that go beyond "traditional" astronomy, including acceleration of particles in various astronomical settings, the origin of cosmic rays, the nature of dark matter, and cosmology in general. The interdisciplinary nature of the field is also reflected in the data collection, reduction, and analysis procedures. As already described in Section 1.1, the experiments employ instrumentation that is familiar both to astronomers (e.g., optical telescopes) and particle physicists (e.g., detectors). In data reduction, cuts are made to separate gamma-ray and cosmic-ray events, which bears resemblance to event selection in a particle physics experiment. The products of data analysis are, however, quite standard in astronomy, such as light curves, spectra, and images.

Since the detection of the Crab Nebula, TeV gamma-ray astronomy has experienced steady, albeit slow at times, growth throughout the 1990s and in the early 2000s, and has matured significantly over the past five years or so, thanks to the availability of a new generation of Cherenkov gamma-ray observatories. The number of sources detected has grown rapidly from a handful to over 70 (Aharonian et al. 2008, and references therein). More significantly, an increasing number of classes of sources have been established as TeV gamma-ray emitters, including BL Lac objects, radio galaxies, quasars, shell-type supernova remnants (SNRs), pulsar wind nebulae (PWNe), X-ray binaries, and stellar clusters, as shown in Figure 2.

Besides discrete sources, large-scale diffuse TeV gamma-ray emission has also been detected along the "Galactic Ridge" (Aharonian et al. 2006d) and in the Cygnus region (Abdo et al. 2007), offering direct evidence for interactions between cosmic rays and molecular clouds. The latter might be a significant contributor to the reported excess of signals in the Cygnus region that could be associated with Galactic cosmic-ray particles and gamma-rays (Amenomori et al. 2006).

2 SCIENTIFIC ACHIEVEMENTS

Much has been learned about the TeV gamma-ray sky over the past two decades. In the following, we will focus on the progress that has been made recently on a few selected topics. This article is meant to provide an update on an earlier review (Cui 2006).

2.1 Origin of Cosmic TeV Gamma Rays

The precise mechanism for producing the detected TeV photons in an astronomical environment is still not entirely understood. It most likely varies from one class of sources to another, or even from one source to another in the same class. The proposed theoretical scenarios fall into two broad categories, leptonic models and hadronic models, although hybrid scenarios have also been put forth. The models differ mainly in the physical nature of gamma-ray emitting particles. Although details vary for different classes of sources, the general features are quite similar.

In leptonic models, TeV gamma-rays are attributed to the inverse Compton (IC) scattering of low-energy photons by relativistic non-thermal electrons (or positrons). The sources of seed photons may originate from synchrotron radiation from the leptons themselves (i.e., synchrotron self-Compton, or SSC for short), or from external radiation fields associated with, e.g., accretion disk, disk corona, companion star, broad-line region, or dusty torus, or from cosmic background radiation, or some combination of these. In hadronic models, the TeV gamma-ray emission is thought to be associated with the decay of π^0, which may be produced in pp or $p\gamma$ interactions, or even with the synchrotron radiation from ultra-relativistic protons in a strong magnetic field in some cases. In reality, it is entirely possible that both leptonic and hadronic processes are operational, thus giving the hybrid scenarios, but not necessarily contributing equally to the observed gamma-ray emission.

A related question is regarding the acceleration of particles in astronomical environments, which is even less understood. It is often assumed that strong shocks are responsible, via the first-order Fermi mechanism. This has provided a theoretical basis for looking for GeV–TeV gamma-rays from sources that are known to produce strong shocks. The approach is fairly successful in practice. The steady-state spectral energy distribution of accelerated particles is determined by the balance of timescales related to acceleration, heating, and cooling processes. For rapidly varying sources, however, non-equilibrium effects may become very important in the study of, e.g., spectral variability. Time-dependent calculations must be performed in such cases.

2.1.1 Active galactic nuclei

Active galactic nuclei (AGNs) were among the first sources detected at TeV energies and have remained the largest source population for TeV gamma-ray astronomy. Initially, the TeV gamma-ray emitting AGNs found were exclusively in BL Lac objects at relatively low redshifts. With lower energy thresholds and better sensitivities offered by the new generation of ground-based gamma-ray observatories, significant progress has been made in recent years on three fronts: (1) much improved quality of multiwavelength data on a few bright TeV blazars for detailed studies; (2) detection of flat-spectrum radio quasars whose gamma-ray output peaks at lower energies than BL Lac objects; and (3) detection of AGNs at higher redshifts.

BL Lac objects and flat-spectrum radio quasars both belong to a sub-class of AGNs, which are known as blazars. Blazars are known to be highly variable across nearly the entire electromagnetic spectrum, producing flares of duration as short as a few minutes or outbursts of duration as long as many months. This, coupled with the non-thermal nature of their emission, implies that the photons from blazars most likely originate in the jets that are directed roughly towards us (Urry & Padovani 1995). Such jet emission, Doppler-boosted in intensity as well as in energy, dominates over radiation from all other sources (e.g., accretion flows). Therefore, blazars are excellent laboratories for studying physical processes in the jets of AGNs (or perhaps of black hole systems in general). Not all blazars have been established as TeV gamma-ray emitters. Those that have invariably shown a characteristic double-peaked spectral energy distribution (SED), with one of the peaks located at keV energies and the other at TeV energies (see Fig. 3 for an example). The two peaks are seen to shift in a correlated manner during a major flare (or outburst). Moreover, both the X-ray and gamma-ray spectra of a blazar tend to become flatter as the source brightens.

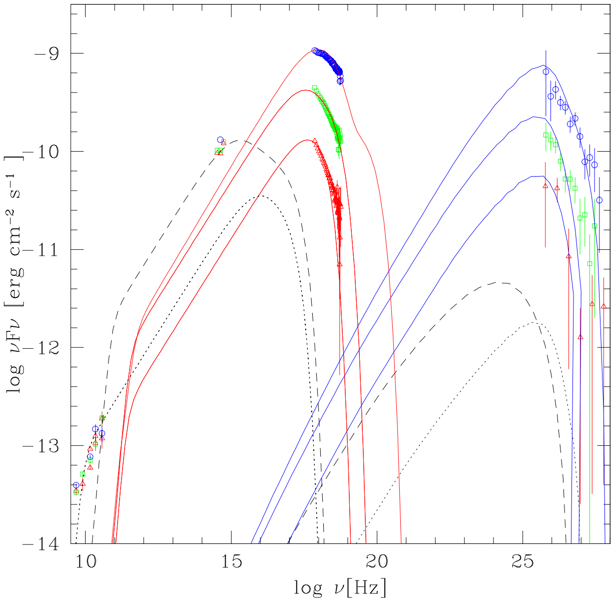

Fig. 3 Spectral energy distribution of Mrk 421. Three sets of flux-averaged SEDs are shown in red, green, and blue, with the flux increasing roughly by a factor of 3 at each step both at X-ray and gamma-ray energies. Note that the optical and radio fluxes vary little. The lines show the results of a multi-zone model. Adapted from Błażejowski et al. (2005).

Various models have been proposed to account for the broadband SED of TeV gamma-ray blazars. Both leptonic and hadronic models attribute the lower-energy SED peak to synchrotron radiation from relativistic electrons (and positrons) in the jets, but they differ on the origin of the higher-energy peak. The leptonic models invoke the IC process to explain the gamma-ray emission from blazars. The seed photons may be the synchrotron photons emitted by the same electrons (e.g., Maraschi et al. 1992; Bloom & Marscher 1996) or originate from sources external to the jet (e.g., Dermer et al. 1992; Sikora et al. 1994). Such models are strongly motivated by the apparent correlation between X-ray and TeV variabilities, as well as by the shape of the measured SEDs. However, the simple (thus commonly used) homogeneous models are increasingly challenged by observations. For instance, it is now quite clear that one-zone SSC models cannot account for the measured broadband SEDs of TeV gamma-ray blazars; more "zones" are almost certainly needed to explain the radio and optical emission (see, e.g., Fig. 3). Also, as the quality of multiwavelength data improves, it has become apparent that the X-ray and gamma-ray correlation is fairly loose (Błażejowski et al. 2005; Horan et al. 2009) or even absent in some cases (Acciari et al. 2009b). Perhaps, the most serious challenge comes from the discovery of TeV gamma-ray flares that either have no counterparts at X-ray energies or are significantly offset in time from their X-ray counterparts (Krawczynski et al. 2004; Błażejowski et al. 2005). The latter are sometimes referred to as "orphan TeV flares", even though they might not be genuinely orphans (see discussion in Błażejowski et al. 2005). Inhomogeneous models have been proposed (e.g., Ghisellini et al. 2005). It remains to be seen whether they can account for all of the observed properties of TeV blazars.

Hadronic processes are more complicated. They could involve proton-induced cascades (Mannheim & Biermann 1992) or *pp* collisions (Dar & Laor 1997; Beall & Bednarek 1999; Pohl & Schlickeiser 2000), but it all boils down to π^0 decay for gamma-ray production (with possible contribution from relativistic leptons via the IC process). For TeV gamma-ray blazars, however, it has been argued that π^0 decay is not important; instead, it is the synchrotron radiation from ultra-relativistic protons in a strong magnetic field that is responsible for the observed TeV photons from blazars (Aharonian 2000; Mücke et al. 2003). The hadronic models are also capable of describing the broadband SEDs of blazars (Aharonian et al. 2005f) and, in principle, of explaining the keV-TeV correlation, if an appreciable amount of X-ray emission comes from synchrotron radiation of *secondary* electrons. There is quite a lot of flexibility in this case, because the co-accelerated, primary electrons might also contribute to the X-ray band in a significant manner. This might explain the scatters in the keV-TeV correlation. However, like the leptonic models, the hadronic models also face the challenges of, e.g., explaining the "orphan" TeV gamma-ray flares.

In an attempt to account for "orphan" TeV gamma-ray flares, Böttcher (2005) invoked a scenario, in which both relativistic electrons and protons play a significant role in gamma-ray production. In this case, the "orphan" TeV gamma-ray flare is caused by relativistic *protons* in the jets interacting with externally reflected synchrotron photons that are associated with an earlier X-ray/TeV flare, which itself is associated with relativistic *electrons* (i.e., synchrotron+SSC) in the jets. The absence of an IC signal expected from the interaction between the relativistic electrons in the jets and the externally reflected photons is attributable to the Klein-Nishina effects. The time interval between the primary X-ray/TeV flare and the "orphan" flare in 1ES 1959+650 appears to be consistent with the propagation of synchrotron photons from the primary flare (to some external cloud and back to the jets), with the chosen model parameters.

One promising and relatively model-independent approach for distinguishing the models is to study the variability of TeV gamma-ray blazars on very short time scales ($< 1\,\mathrm{h}$). Such rapid variability was first seen in Mrk 421 at TeV energies in the form of a spectacular flare (Gaidos et al. 1996). Similar flares have also subsequently been observed at keV energies (Cui 2004). In fact, the high-quality X-ray data have unveiled a hierarchical nature of the flaring phenomenon. As illustrated in Figure 4, X-ray flares are seen on a vast range of time scales. Comparing to Mrk 501, it seems that the more frequently flaring occurs on one time scale the more frequently it does on other time scales (Xue & Cui 2005). Very recently, TeV gamma-ray variability has been observed on a time scale of minutes in PKS 2155–304 (Aharonian et al. 2007b) and Mrk 501 (Albert et al. 2007). On general physical grounds, these minute-scale TeV

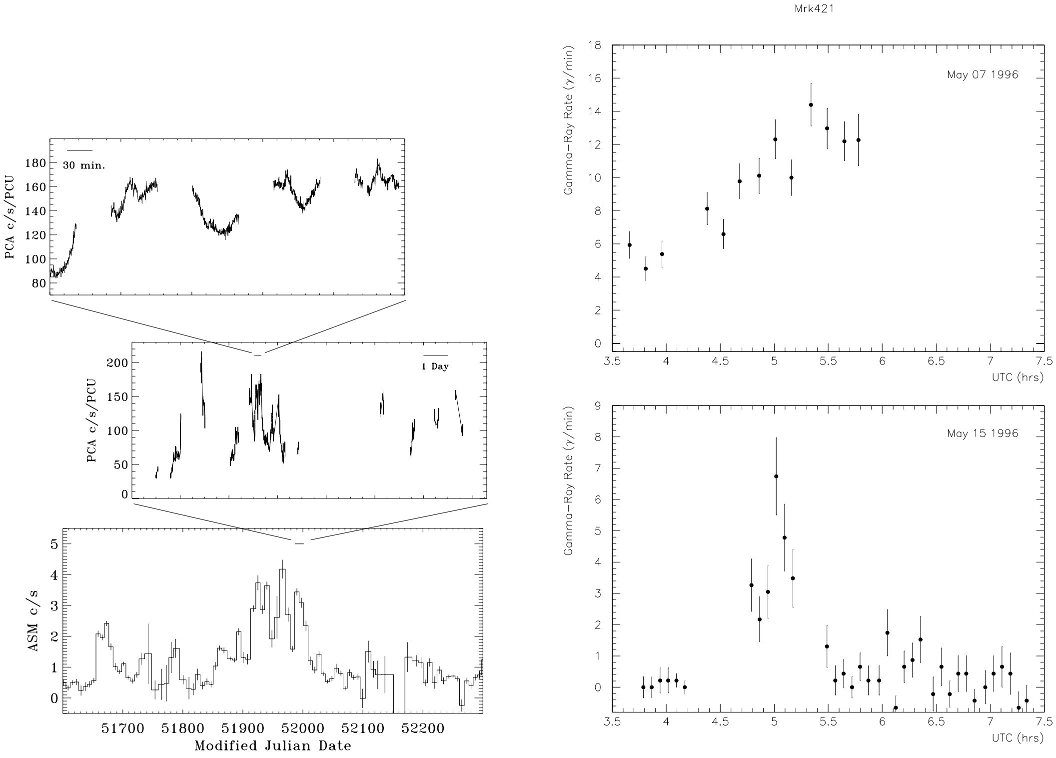

Fig. 4 Flaring activities of Mrk 421. (*left*) X-ray flaring hierarchy (taken from Cui 2004); (*right*) Rapid TeV flares (taken from Gaidos et al. 1996).

gamma-ray flares are very difficult (if at all possible) to be accomodated by the proton-synchrotron mechanism — an unreasonably large magnetic field would be required to match the synchrotron cooling time of the protons to the observed variability time scale.

The minute-scale gamma-ray flares present a challenge to leptonic models as well. For instance, the observed TeV flare from PKS 2155–304 not only implies a highly compact emission region (comparable to the Schwarzschild radius of a $10^9\ M_\odot$ black hole!) but imposes a *lower* limit on the Doppler factor of bulk motion ($>$100), which is uncomfortably large (based on distributions derived from radio observations). The problem may be alleviated by introducing additional features to the models, such as radiative deceleration of jets (Levinson 2007). On the other hand, a large Doppler factor would argue in favor of external IC processes (Begelman et al. 2008). The added complexity offers more “wiggle room” in applying the models to the data. Simultaneous SED modeling helps in providing additional constraints but much degeneracy tends to remain. The situation can be improved by having a sufficiently large sample of rapid flares seen both at keV and TeV energies. This has remained an observational challenge, because it requires dedicated monitoring at the two wavebands, as well as a lot of good luck!

On the theoretical front, the precise mechanism that causes flaring in blazars is not yet understood. The flares could be ultimately related to internal shocks in the jets (Rees 1978; Spada et al. 2001), or to major ejection of new components of relativistic plasma into the jet (e.g., Böttcher et al. 1997; Mastichiadis & Kirk 1997), or to magnetic reconnection events (like solar flares; Lyutikov 2003). The amplitude and duration of flares probably reflect the energetics and physical timescales involved in the processes. The SED of a TeV gamma-ray blazar is known to evolve significantly during a major outburst (or flare with a duration of weeks to months). Both the X-ray and gamma-ray spectra tend to flatten as the source brightens (e.g., Xue et al. 2006; Krennrich et al. 2002; see, however, Acciari et al. 2009b). It has been shown that the observed X-ray spectral variability requires a change in multiple key physical parameters (Xue et al. 2006), including the total energy, spectral index, and maximum Lorentz factor of synchrotron emitting electrons, as well as the magnetic field, as opposed to any single parameter (as argued by Konopelko et al. 2003).

At present, the proposed models for blazars are still at a stage of *assuming* a spectral energy distribution for radiating particles. No detailed treatment of particle acceleration is usually made. It is a common practice to adopt a simple power law for the particle distribution, although a more sophisticated treatment, taking into account the balance among acceleration, heating, and cooling of the particles, leads to more complicated distributions. In principle, the observed gamma-ray spectrum of blazars imposes constraints on the particle acceleration process in either leptonic or hadronic scenarios. To this end, a recent surprise is the unusually hard *intrinsic* gamma-ray spectrum of blazars at moderate redshifts. To obtain the intrinsic spectrum, one must correct for the effects of gamma-ray absorption due to diffuse infrared background radiation (see Sect. 2.2). Even for minimal possible absorption, the intrinsic gamma-ray spectrum of, e.g., 1ES 1101–232, is found to be extremely hard (Aharonian et al. 2006e). This may have a profound impact on our understanding of particle acceleration in the jets of AGNs.

Until very recently, BL Lac objects represented the only type of AGN that is seen to emit TeV gamma-rays. With the detection of 3C 279 (Errando et al. 2008), flat-spectrum radio quasars have now emerged as a viable source population for TeV gamma-ray astronomy. Equally significant is the discovery of BL Lac objects, such as W Comae and 3C 66A (Acciari et al. 2008a, 2009a), whose SED peaks are located in between the traditional TeV BL Lac objects and flat-spectrum radio quasars, as the observation begins to cover the entire continuum of the blazar phenomenon.

The only AGNs that have been detected at TeV energies and are not a blazar are M 87 (Aharonian et al. 2003; Acciari et al. 2008b; Albert et al. 2008a) and Cen A (Aharonian et al. 2009). Both sources are classified as an FR I radio galaxy. For quite some time, M 87 is thought to be a source of ultra-high-energy particles (Ginsburg & Syrovatskii 1964). In this sense, the detection of M 87 at TeV energies is not a total surprise. As in the case of blazars, the TeV gamma-ray emission from M 87 has also been modeled both in the leptonic and hadronic scenarios. In the leptonic model, M 87 is simply viewed as a "mis-aligned blazar" (Bai & Lee 2001), with the TeV gamma-rays originating in the IC process.

More recently, M 87 has been seen to vary on a timescale of days at TeV energies (Aharonian et al. 2006h), implying a very compact region of gamma-ray production in the immediate vicinity of the black hole. The previously favored HST-1 hot spot (e.g., Stawarz et al. 2006) appears to have been ruled out by the observed gamma-ray variability. The new variability constraints have prompted the development of more sophisticated leptonic models (Lenain et al. 2008; Tavecchio & Ghisellini 2008). Alternatively, the hadronic models attribute the gamma-rays to synchrotron radiation from protons (Protheroe et al. 2003). Such models have not been scrutinized with observations as much as the leptonic models.

In many ways, Cen A is similar to M 87, so the same physical processes might also operate in this source. Being the nearest active galaxy known, its inner jet structures could be resolvable with the next-generation gamma-ray experiments and might thus offer an excellent laboratory for studying particle acceleration in the immediate vicinity of black holes.

2.1.2 Pulsars, pulsar wind nebulae and supernova remnants

The Crab Nebula is the first pulsar wind nebula (PWN) detected at TeV energies. The TeV gamma-ray emission is still spatially unresolved, although the bulk of the emission is clearly associated with the pulsar wind. Only very recently, the MAGIC collaboration reported the detection of gamma-rays from the pulsar itself, with the help of a special triggering scheme (Aliu et al. 2008). This is a highly significant result, because it may shed much light on the issue of gamma-ray production in pulsars, which has been a long, intense debate since the detection of pulsars by EGRET.

Pulsars have long been suspected to be a source of Galactic cosmic-ray electrons, so seeing gamma-rays from them is not a surprise in itself. The prospect of using the gamma-rays to study particle acceleration and radiative processes in a neutron star environment is, on the other hand, very exciting. Now that the first results from *Fermi* on pulsars seem to rule out an origin of gamma-rays near the polar cap of neutron stars, at least for some pulsars (Abdo et al. 2009a), there is more hope to see additional pulsars at TeV energies.

The first source showing extended TeV gamma-ray emission is RX J1713.7–3946 (Aharonian et al. 2004a), a shell-type SNR. The exquisite gamma-ray image obtained of the source (as shown in Fig. 5) has, in our view, truly elevated the field to a new level. For the very first time, imaging is carried out at a resolution of arcminutes at TeV energies. Not only has this enabled morphological studies of extended gamma-ray emission over multiple wavebands, it is also critical for cross-band identification of new source populations. To put things in prospective, the nature of gamma-ray bursts (GRBs) had remained elusive until imaging of their X-ray afterglows reached a resolution of arcminutes with *BeppoSAX*. The number of TeV gamma-ray emitting PWNe and SNRs has been increasing rapidly in over the past five years. They are the dominant population among Galactic TeV gamma-ray sources.

The discovery of TeV gamma-ray emission from SNRs has brought a sigh of relief for many in the field, because it is almost taken for granted that they are the main source of Galactic cosmic rays. However, direct evidence for relating the observed gamma-rays to hadronic processes is still lacking, because the observed gamma-ray emission can be accommodated by both leptonic and hadronic scenarios (not without issues in either case). In leptonic models, TeV photons are thought to be produced in the IC scattering of mainly CMB photons by relativistic electrons that are accelerated by a strong shock at the outer edge of an SNR (e.g., Aharonian et al. 2006b, 2005a; Brogan et al. 2005), although other sources of seed photons (e.g., star light) may be needed in some cases to account for the observed broadband SED. For RX J1713.7–3946, the leptonic models can naturally explain the observed spatial coincidence between the X-ray and TeV emitting regions, since X-ray photons are attributed to synchrotron radiation from the same electrons. Quantitatively, however, a low magnetic field ($B < 15\,\mu$G) in the shell would be required to account for the observed SED (Aharonian et al. 2006b), which appears to be at odds with the observed X-ray variability associated with the shell on a timescale of about a year (Uchiyama et al. 2007).

On the other hand, the observed TeV emission from SNRs can also be explained as the product of the decay of neutral pions that are produced in the collision between relativistic protons and the surrounding medium (Aharonian et al. 2006b). In this case, the challenge is to account for the observed X-ray/TeV spatial correlation. One can either attribute X-rays to synchrotron radiation from *co-accelerated* electrons or invoke correlated enhancement of the magnetic field and the density of the surrounding medium (Aharonian et al. 2006b). At present, it is fair to say that no conclusive evidence exists for the acceleration of protons in SNRs. Somewhat disturbingly, this is not due to insufficient quality of the gamma-ray data. For instance, the gamma-ray spectrum of RX J1713.7–3946 is of high quality over three decades in energy, from about 0.1 TeV to nearly 100 TeV (Aharonian et al. 2007a)! In this particular case, however, the multiwavelength observations seems to favor a hadronic origin (Tanaka et al. 2008), because it provides a more reasonable fit to the SED and can also explain the year-scale X-ray variability.

For PWNe, leptonic scenarios are more likely, as supported by similar morphologies at keV and TeV energies. The X-ray emission is associated with synchrotron radiation from relativistic electrons, while TeV gamma-rays are produced via IC processes, with seed photons coming mainly from the CMB (e.g., Aharonian et al. 2005b,d, 2006a,f). Intriguingly, however, there are also cases in which there is little morphological correspondence between TeV gamma-ray and X-ray images. Figure 6 shows such an example. The connection between HESS J1825–137 and the PWN associated with PSR B1823–13 was made based on similar asymmetric distributions at TeV and keV energies roughly along the north-south direction (Aharonian et al. 2005d). However, the gamma-ray emission is much more extended than the X-ray emission, and the two are significantly offset from each other. This has added uncertainty to the identification of a few TeV gamma-ray sources that are in the vicinity of pulsars (and might thus been associated with PWNe; e.g., Cui & Konopelko 2007; Chang et al. 2008). Plausible causes for the morphological differences have been suggested (Aharonian et al. 2005d). We think that the challenge is to explain, in a natural way, why the processes (e.g., diffusion beyond the PWN boundary) are not operating in systems in which the X-ray and gamma-ray images match well.

2.1.3 X-ray binaries

From a historical perspective, X-ray binaries have played a crucial role in the development of TeV gamma-ray astronomy. They are among the very first sources that were claimed to be TeV gamma-ray emitters in the 70 s and 80 s. The chain reaction fueled by such claims helped generate and sustain the momentum to develop more sophisticated experiments and data analysis techniques, which ultimately led to the establishment and success of an exciting field. It is, however, ironic that none of the early claimed detections of X-ray binaries are now deemed credible, because the sources have not been seen with the new and much more sensitive experiments over the past two decades or so. While one could always invoke a once-in-a-lifetime transient phenomena to explain away the modern non-detections, it would seem to be too much of a coincidence for the source population as a whole to cooperate in such a way!

It was not until several years ago that the first credible detection of an X-ray binary (PSR B1259–63) was reported (Aharonian et al. 2005e). The source consists of a 48-ms radio pulsar and a Be star in a highly eccentric orbit (with a period of ∼3.4 yr). Be stars are known to be fast rotators that produce a dense equatorial wind. When the neutron star passes through the wind, enhanced accretion onto the neutron star (due to the capture of wind) is thought to be responsible for the activities previously seen in the X-ray and soft gamma-ray bands . Moreover, the collision between pulsar wind and stellar wind could result in the formation of a strong shock, which is not fundamentally different from the formation of PWN, although the wind dynamics in a binary system are certainly different from those around an isolated neutron star.

The observed TeV gamma-rays may originate in the relativistic electrons that are accelerated by the shock via the IC process. In this case, however, the seed photons are likely dominated by radiation from the Be star. Given that, one would expect strong orbital modulation of the TeV gamma-ray emission, which appears to be present. Also, the TeV gamma-ray emission is seen to vary significantly over the orbit, as shown in Figure 7. It is interesting to note that the TeV emission appears to be at a lull at the periastron passage. In general, the observed light curve is not compatible with simple IC scenarios (Aharonian et al. 2005e). No detailed hadronic modeling has been performed. Given the presence of a dense wind disk around the Be star, the *pp* process might be quite efficient here, producing neutral pions, which then decay to produce the detected gamma-rays (Kawachi et al. 2004).

During its survey of the Galactic central region, HESS discovered another X-ray binary, LS 5039 (Aharonian et al. 2005g). The source stood out as the only point-like source detected in the survey. It is only about 1° away from HESS J1825–137 (a likely PWN), which again illustrates the necessity of high-resolution imaging for such a discovery. LS 5039 was originally identified by Motch et al. (1997) using ROSAT data as a likely High Mass X-ray Binary (HMXB) system, with an O7V(f) luminous companion at a distance of 3 kpc. The nonthermal synchrotron radio emission was later discovered by Martí et al. (1998) using the Very Large Array (VLA). The RXTE observations performed by Ribó et al. (1999) show a hard X-ray spectrum extending up to 30 keV, which can be fitted satisfactorily with a power-law (plus a strong iron line centered at 6.6 keV). Radio interferometric observations with the Very Long Baseline Array (VLBA) by Paredes et al. (2000) resolved the source into milliarcsecond bipolar radio jets, suggesting that LS 5039 might be a microquasar. This is supported by dynamical measures that seem to favor the presence of a black hole of 3.7 $M_\odot$ in the system (Casares et al. 2005b), although the uncertainty is still quite large.

The orbital period of LS 5039 is only about 3.9 days, so it is relatively easy to quantify the orbital effects on gamma-ray production (compared to PSR B1259–63). As shown in Figure 8, not only has the modulation of the gamma-ray flux been well established along the binary orbit, the observed gamma-ray spectrum also shows a very intriguing pattern of variability (Aharonian et al. 2006g). The pattern is not easy to understand in a natural way; it might simply reflect, at least partially, a change in the spectral energy distribution of radiating particles along the orbit (e.g., Sierpowska-Bartosik & Torres 2009b).

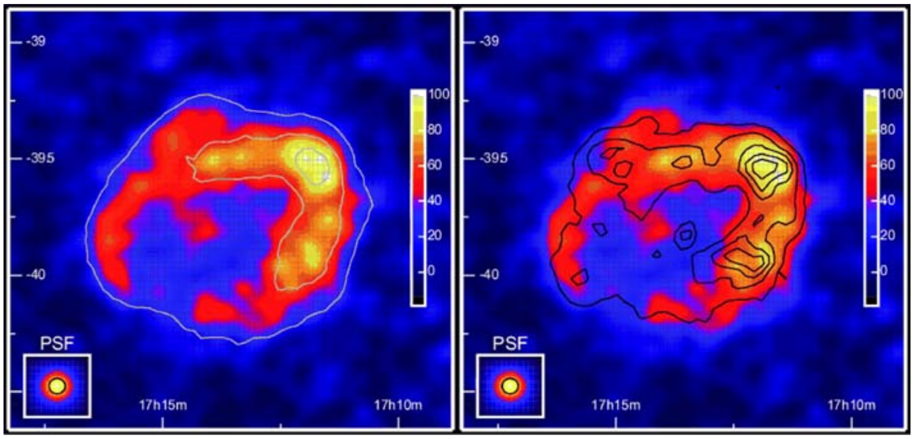

Fig. 5 TeV gamma-ray image of the supernova remnant RX J1713.7–3946. The superimposed contours show the significance (*left*) and 1–3 keV X-ray surface brightness (*right*), respectively. Taken from Aharonian et al. (2007a).

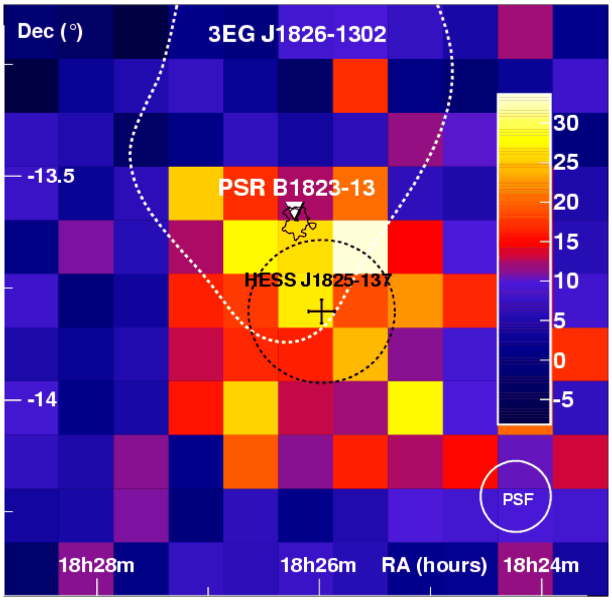

Fig. 6 TeV gamma-ray image of HESS J1825–137. The cross shows the best-fit centroid of the gamma-ray excess, while the black dotted circle shows the best-fit 1σ emission region size assuming a Gaussian brightness profile. The position of PSR B1823–13 is indicated by the white triangle. The black contours denote the X-ray emission. The 95% confidence region (dotted white line) for the position of the unidentified EGRET source 3EG J1826–1302 is also shown. Taken from Aharonian et al. (2005d).

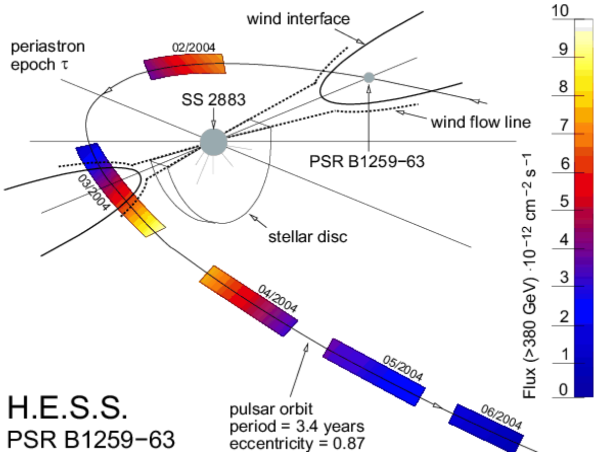

Fig. 7 Variable TeV gamma-ray emission from PSR B1259–63 over the binary orbit. Taken from Aharonian et al. (2005e).

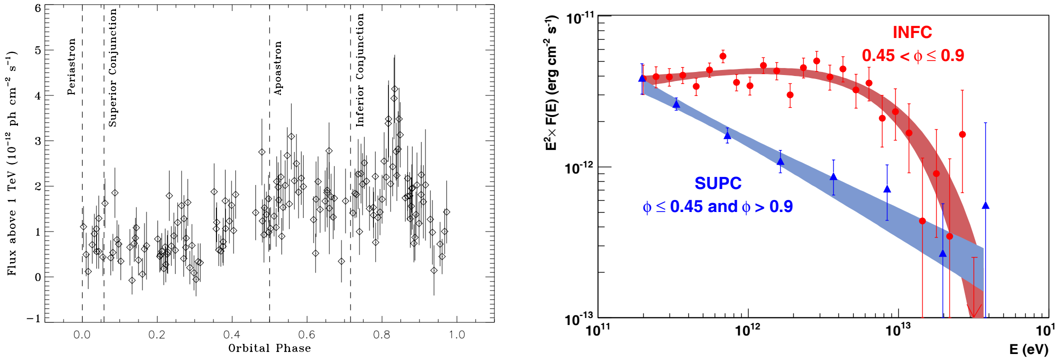

Fig. 8 Variable TeV gamma-ray emission from LS 5039 over the binary orbit: (*left*) folded light curve and (*right*) gamma-ray spectra. Taken from Aharonian et al. (2006g).

Of course, other effects are also expected to play a significant role in causing the orbital modulation of gamma-rays, including anisotropic IC scattering, attenuation due to $\gamma\gamma$ pair production and subsequent electromagnetic cascading, and adiabatic losses (e.g., Khangulyan et al. 2008).

The enigmatic gamma-ray source LS I +61 303 has also recently been seen to emit TeV gamma-rays (Albert et al. 2006a; Acciari et al. 2008c). Like LS 5039 and PSR B1259–63, it falls in the category of high-mass X-ray binaries (HXMBs). The nature of the compact object is even less certain in this case than LS 5039. It was initially argued to be a neutron star although a more recent study has shown that it could also be a black hole, given the uncertainty in the inclination of the binary system (Casares et al. 2005a). On the other hand, the binary parameters are well determined. The companion star is a Be star, as in the case of PSR B1259–63. It is in an eccentric orbit ($e \approx 0.7$) with the compact object, with an orbital period of 26.4960 days, which is determined from the observed periodic modulation of the radio emission (Gregory 2002). For reference, the periastron passage occurs at Phase 0.23.

For a long time, LS I +61 303 is thought to be the counterpart of 2CG 135+01, a COS-B source, and more recently that of 3EG J0241+6103, an EGRET unidentified source. If the latter association is real, the EGRET observations would indicate that the source also varies significantly over the binary orbit also at GeV energies. Significant variability is now well established at TeV energies (Albert et al. 2006a; Acciari et al. 2008c), although it is not entirely clear whether it is entirely related to the orbital motion (however, see Albert et al. 2009). What is most surprising is the fact that the TeV gamma-ray flux peaks near the *apoastron* passage (i.e., when the compact object is farthest from the Be star), because, at longer wavelengths, Be binaries tend to become active near the *periastron* passage, presumably due to enhanced accretion from the stellar wind. In principle, the gamma-ray lull near the periastron passage could be the manifestation of $\gamma\gamma$ attenuation (in the intense stellar radiation field), even though gamma-ray production is expected to be high as well (either via the IC process in leptonic scenarios or pp collisions in hadronic scenarios). Calculations have shown that, with the right choice of parameters, the observed variability can be accounted for (Sierpowska-Bartosik & Torres 2009a).

It is worth noting that the three X-ray binaries detected at TeV energies are all HMXBs. Observationally, accreting X-ray pulsars tend to be found in HMXBs, especially in Be systems. Whether there is a causal connection between the two remains to be seen. The interaction between pulsar wind and stellar wind certainly provides a plausible mechanism for accelerating particles to high energies, which then radiate TeV gamma-rays. On the other hand, microquasars are predominantly low-mass X-ray binaries (LMXBs), including some of the most spectacular systems, such as GRS 191+105, that give rise to the name "microquasar". From a theoretical point of view, the jets in microquasars are certainly promising sites for particle acceleration and gamma-ray production. The presence of non-thermal particles in the jets is well established by observations at longer wavelengths (radio and X-ray in particular). However, no LMXB has been seen at TeV energies (or GeV energies). This could be due to the lack of (stellar) seed photons for the IC process in leptonic scenarios, or the lack of strong stellar wind for pp collisions in hadronic scenarios, or the lack of particles at sufficiently high energies. The observations appear to disfavor the SSC process, because the jets seem more energetic and prominent in LMXBs than in HXMBs.

To make progress, a systematic observational effort is required not only to increase the number of TeV gamma-ray emitting X-ray binaries but also to collect *simultaneous* multiwavelength data. A reliable SED would establish at which wavelengths a source radiates most of its power, which is an important step towards understanding radiation mechanisms. To date, modeling efforts have mainly been based on multiwavelength data taken at different times. Given that X-ray binaries are known to vary on a wide range of timescales, the results should be taken with a grain of salt.

2.1.4 Unidentified TeV gamma-ray sources

Arguably the most intriguing recent development in the field is the discovery of a population of TeV gamma-ray sources that appear to have no counterparts at longer wavelengths. Of course, *unidentified* does not necessarily imply *unidentifiable* or the lack of plausible counterparts. The presently unidentified TeV gamma-ray sources cluster around the Galactic plane, indicating that they are likely of Galactic origin. Moreover, most of them are spatially extended, suggesting that they might be associated with unseen PWNe or SNRs, given that PWNe and SNRs constitute the largest populations of Galactic TeV gamma-ray sources. Indeed, a number of previously unidentified gamma-ray sources have subsequently been found to be probably associated with SNRs or PWNe (e.g., Aharonian et al. 2006i, 2005; Cui & Konopelko 2007; Tian et al. 2008; Chang et al. 2008).

TeV J2032+4130 is the first *bona fide* unidentified TeV gamma-ray source and has remained as such. It was accidentally discovered by the HEGRA Collaboration (Aharonian et al. 2002), in an intense campaign which studied Cygnus X-3. The initial detection was only of marginal statistical significance but has since been confirmed by multiple experiments (Aharonian et al. 2005h; Konopelko et al. 2007; Albert et al. 2008b). The HEGRA results indicated that TeV J2032+4130 was an extended TeV gamma-ray source, with a Gaussian radius of $6.2' \pm 1.2'_{\rm stat} \pm 0.9'_{\rm sys}$, and the center-of-gravity (CoG) of the gamma-ray emission lay roughly 0.5° north of Cygnus X-3. The measured gamma-ray spectrum was hard, with a power-law photon index of –1.9. These results have since been confirmed by the MAGIC measurements.

The situation is complicated by a reported detection of TeV J2032+4130 at a significantly higher flux by the Whipple Collaboration (Lang et al. 2004), based on archival observations. The difference in flux could be explained by variability of the source over a time scale of years but it would seem to be at odds with the extended nature of the TeV gamma-ray emission. One could speculate about the presence of another variable gamma-ray source that is located very close to TeV J2032+4130. It is worth noting that the peak of the gamma-ray emission detected with *Whipple* appears to be offset by that from the HEGRA position by about $3.6'$, although the uncertainty is quite large. The gamma-ray flux derived from more recent Whipple observations of TeV J2032+4130 is much closer to the HEGRA flux (Konopelko et al. 2007).

TeV J2032+4130 lies in the general direction of Cygnus OB2, a rich cluster of OB stars less than 2 kpc away. For a long time, it has been thought that the winds of massive stars in such a cluster carry a sufficient amount of energy that, when released, may power the production of very-high-energy (VHE) gamma-rays through the production of neutral pions in the collisions between non-thermal ions (accelerated by the shocks in the winds) and thermal protons in the winds (White & Chen 1992; Torres et al. 2004). Even among the most massive star clusters, Cygnus OB2 represents an extreme case — it is the most massive stellar association known in the Galaxy, containing about 2600 OB stars (Knödlselder 2000). It is, therefore, natural to speculate about a plausible physical connection between TeV J2032+4130 and Cygnus OB2 (Torres et al. 2004). However, Cygnus OB2 represents quite a large region in the sky.

Very recently, a catalog of bright gamma-ray sources has been released that contain all sources detected at a statistical significance of $> 10\sigma$ with the Large Area Telescope (LAT) on board the *Fermi Gamma-ray Space Telescope* (Abdo et al. 2009b). In it, 0FGL J2032.2+4122 lies only about $8'$ from the CoG of TeV J2032+4130. Note that the 95% error radius of the LAT position of the source is determined to be $5.1'$ and that an overall uncertainty in the position of TeV J2032+4130 is about $3'$. Therefore, 0FGL J2032.2+4122 is a promising candidate for being the GeV counterpart of TeV J2032+4130, based on spatial coincidence alone.

Interestingly, 0FGL J2032.2+4122 is one of the 29 gamma-ray pulsars detected by *Fermi* LAT (Abdo et al. 2009b). It is designated as LAT PSR J2032+41, because it falls in a special category of pulsars which seem to only show pulsation in the gamma-ray band. The discovery of such pulsars is a major highlight at the early stage of the *Fermi* mission. Being "dark" at longer wavelengths, these sources could have easily escaped previous pulsar searches or surveys. They also provide a natural explanation for some of the unidentified gamma-ray sources, such as TeV J2032+4130, now that PWNe constitute a major population among VHE gamma-ray emitters. Additional support for the PWN nature of TeV J2032+4130 comes from the detection of extended X-ray emission that spatially coincides with TeV J2032+4130, based on a deep exposure of the region with the *XMM-Newton* (Horns et al. 2007). The X-ray feature is said to be similar in extent to TeV J2032+4130. The X-ray spectrum is also very hard, with a power-law photon index of –1.5. The overall X-ray power output is comparable to the TeV gamma-ray power of TeV J2032+4130.

The significance of establishing a connection between TeV J2032+4130 and LAT PSR J2032+41 goes far beyond identifying an unidentified gamma-ray source. The gamma-ray-only pulsars discovered by *Fermi* may represent the tip of the iceberg of a population of such sources. This would imply that other unidentified TeV gamma-ray sources might simply be PWNe associated with these "dark" pulsars and thus provide the answer to a long-standing question on the nature of unidentified gamma-ray sources (from the EGRET days to the TeV gamma-ray era). The fact that nearly all unidentified gamma-ray sources are extended is consistent with such a scenario. A systematic investigation on the subject, utilizing data both from *Fermi* and ground-based TeV gamma-ray observatories, may prove fruitful in unveiling such connections.

One complication in identifying the unidentified TeV gamma-ray sources arises from the fact that the morphology of the sources may look different at longer wavelengths. This is perhaps best illustrated by the association of HESS J1825–137 with the PWN G18.0–0.7 (Aharonian et al. 2006i). The gamma-ray emission spreads over a much larger region than the X-ray emission from the PWN (see Fig. 6). Moreover, the pulsar (PSR B1823–13) is offset from the center of the PWN (which in turn is offset from the CoG of the gamma-ray emission). It is the similar asymmetry in the X-ray and gamma-ray emission with respect to the pulsar that provides additional evidence for a PWN origin of HESS J1825–137. Cases like this are not uncommon (e.g., Cui & Konopelko 2007; Chang et al. 2008), which makes arguments based on spatial coincidence alone suspect. This is certainly an area to which improved sensitivity and angular resolution can add much.

2.2 Impact on Cosmology

TeV photons may interact with infrared photons to produce electron-positron pairs and thus be effectively "absorbed". This process must be taken into account in modeling the SED of all TeV gamma-ray sources. Cosmologically, the implication is that the visible TeV gamma-ray sky does not extend very far, due to the presence of permeating infrared background radiation. On the other hand, we could use distant TeV gamma-ray sources as cosmic beacons to probe the diffuse infrared background, which has remained an observational challenge for direct measurements. Since the background radiation contains important information about star formation in the early universe and the subsequent evolution of galaxies, the derived constraints on the diffuse infrared background can have serious cosmological implications.

An early surprise coming out of recent TeV gamma-ray observations is the realization that the universe seems to be much more transparent at TeV gamma-ray energies than what was previously thought or, equivalently, the infrared background is much less intense (Aharonian et al. 2006e). The results were initially based on gamma-ray observations of two blazars at moderate redshifts. At the wavelengths of $\sim$1–3 μm, the derived upper limit is barely above the level of integrated light from the galaxies that has already been resolved by *Spitzer*. This has since been confirmed by independent measurements (Aharonian et al. 2007c, d; Albert et al. 2008).

The results can be enhanced in two ways. One is to extend the spectral coverage both to lower and higher energies (beyond 1 TeV), to extend the constraints on the IR background over a broader spectral range; the other is to observe a large sample of blazars at a range of redshifts, to separate intrinsic and extrinsic effects on the gamma-ray spectrum of blazars. The latter is obviously also important for understanding gamma-ray production and propagation in blazars. Meaningful enhancements will likely require a significant improvement in the sensitivity of gamma-ray observations, as well as in the discovering capability of the next-generation of observatories.

On a different front, despite intense observational efforts, the search for dark matter signals has not yielded any meaningful constraints on theoretical models. The detection of TeV gamma-rays from the direction of the Galactic center (Tsuchiya et al. 2004; Kosack et al. 2004; Aharonian et al. 2004b) generated a great deal of excitement about the prospect of finally seeing, albeit indirect, evidence for the annihilation of dark matter particles (Horns 2005), since the region had been thought of as the best place to search for gamma-ray emission resulting from such signals (Berezinsky et al. 1994; Bergstrom et al. 1998, 2001; Cesarini et al. 2004; Hooper & Dingus 2004). However, it was quickly realized that more mundane explanations involving SNRs or PWNe would be more viable (Wang et al. 2006). This is a generic problem with targets (such as the central region of galaxies, clusters of galaxies, etc.) in which there exist plausible astronomical TeV gamma-ray emitters.

A more promising class of systems for indirect dark matter searches are dwarf spheroidal galaxies (e.g., Gilmore et al. 2008), which have much larger mass-to-light ratios than normal galaxies. They have indeed become a focus of recent observational efforts (Wood et al. 2008; Albert et al. 2008c; Aliu et al. 2009). To date, no positive detection has been reported.

2.3 Impact on Cosmic Ray Physics

The origin of cosmic rays has remained an unresolved issue. For cosmic rays below $\sim 10^{15}$ eV, it is almost taken for granted that they are associated with SNRs in the Galaxy. Strong shocks at the outer edge of SNRs are naturally thought of as the site for particle acceleration. If it is the case, SNRs ought to be among the most promising targets for TeV gamma-ray experiments. It is reassuring, therefore, that an increasing number of SNRs have been detected at TeV energies. Unfortunately, this success has not led to a direct proof of the production of cosmic rays in SNRs, because, as discussed in Section 2.1.2, the observed gamma-rays could be accommodated by either a leptonic or hadronic scenario. It is, however, hopeful that as the quality of data improves, the observations may begin to unveil the characteristics of π^0 decay.

On the other hand, the detection of diffuse TeV gamma-ray emission in the Cygnus region and around the Galactic Ridge has provided direct evidence for interactions between cosmic rays and molecular clouds in the Galaxy (Abdo et al. 2007; Aharonian et al. 2006d). The excellent spatial correlation between the Galactic Ridge emission and molecular clouds has left little room for an alternative explanation. The measured gamma-ray spectrum indicates that the spectrum of cosmic rays near the center of the Galaxy is significantly harder than that in the solar neighborhood, presumably a propagation effect (Aharonian et al. 2006d). Moreover, the density of cosmic rays seems to be many times the local density. It is argued that the observations can be explained by the presence of a particle accelerator near the Galactic center that has been active over the past 10^4 yr. An obvious candidate is the supernova remnant Sgr A East, which has about the right age. Moreover, Sgr A East is a plausible counterpart of HESS J1745–290, whose TeV spectrum has a similar shape to the spectrum of the diffuse emission.

3 CONCLUDING REMARKS

The field of TeV gamma-ray astronomy has matured immensely in recent years and has become a viable branch of modern astronomy. It provides a unique window to the extreme non-thermal side of the universe. Many classes of astronomical systems have been detected at TeV energies. The observations have not only shed new light on the properties of the systems themselves but also on the physical processes operating in diverse astronomical settings. For instance, taken together, Blazars, microquasars, and gamma-ray bursts (though none have been detected at TeV energies yet; Atkins et al. 2005; Albert et al. 2006b; Horan et al. 2007) may offer an excellent opportunity for us to make some tangible comparisons of the processes of particle acceleration and interaction in the jets of black holes over a vast range of physical scales (from microparsecs to megaparsecs; Cui 2005). As the capability of TeV observatories improves, it is hopeful that more sources in the established classes and, more importantly, new classes of sources (e.g., GRBs, clusters of galaxies, etc.) will be detected.

The field is of equally great interest to physicists, because it has made it possible to study some of the most important questions in physics at energies much beyond the capabilities of present and future particle accelerators. Independent of theoretical scenarios, TeV observations are capable of constraining the intrinsic spectrum of emitting particles and thus casting light on the nature of the particles and on the acceleration mechanisms. TeV observations have already begun to have a serious impact on modern cosmology. They have also provided insights into such fundamental issues as dark matter, evaporation of primordial black holes, and tests of Lorentz invariance. The constraints are expected to improve as the quality of data improves. In some cases, however, the challenge is to separate astronomical and physical origins of the detected TeV photons.

4 FUTURE PERSPECTIVE

It is perhaps instructive to compare the development of TeV gamma-ray astronomy with that of X-ray astronomy. Table 1 shows roughly similar stages in the development of the respective fields. We think that TeV gamma-ray astronomy is roughly where X-ray astronomy was in the *Einstein* days, when direct fine imaging became possible for the very first time. Coincidentally, it took both fields about the same

Table 1 Development of X-ray Astronomy and TeV Gamma ray Astronomy

Stages	X-ray Astronomy	TeV Gamma-ray Astronomy
initial activities	sounding rocket and balloon experiments	Cherenkov and air shower experiments
first detection	Sco X-1	Crab Nebula
follow-ups	more detections	more detections
first survey	Uhuru satellite	Milagro
direct fine imaging	Einstein satellite	HESS, VERITAS
further development	Ariel 5, ROSAT, ASCA, etc.	HAWC? LHAASO? CTA? AGIS?
state-of-the-art survey	ROSAT all-sky survey	HAWC? LHAASO?
wide- and narrow-field combo	RXTE, Swift	LHAASO?
state-of-the-art imaging	Chandra, XMM-Newton	CTA? AGIS?

amount of time to reach this stage of development, following the detection of the first extra-solar source. A noteworthy difference is that an all-sky survey had been conducted with the *Uhuru* satellite, before the *Einstein* satellite was put in orbit, at a flux limit that is several orders of magnitude below the fluxes of the X-ray sources detected at the time. Although a full-sky survey had also been carried out at TeV energies with *Milagro* (and also *Tibet AS*γ), before HESS came online, the flux limit reached is only comparable to the brightest TeV sources known at the time (Atkins et al. 2004).

The *Uhuru* survey provided much needed guidance to subsequent X-ray missions. It was superseded in the 90s by a much more sensitive survey carried out with the *ROSAT* satellite. The *ROSAT* survey saw nearly all classes of astronomical sources, from stars to AGNs to clusters of galaxies, and is truly a key milestone in the development of X-ray astronomy. We believe that a similar comprehensive survey is imperative to the development of TeV gamma-ray astronomy. A glimpse of the importance of such a survey is provided by the HESS survey of the Galactic central region (Aharonian et al. 2005c, 2006c). Though very limited in scope, the HESS survey has led to many of the most exciting recent discoveries in the field. This implies that a full-sky survey with roughly the sensitivity of *HESS* would be needed to unveil what is below the tip of the iceberg already seen.

Two wide-field surveying experiments have been proposed, based on the water Cherenkov technique that was pioneered by the *Milagro* collaboration which was proven to be remarkably successful. The High Altitude Water Cherenkov (*HAWC*)[1] experiment is to be located in Sierra Negra, Mexico, which is about 4100 m above sea level. In the proposed configuration, *HAWC* is expected to be 10–15 times more sensitive than *Milagro*. Being a ground-based experiment, it would be easily expandable (by adding more water tanks) and thus become more sensitive. The Large High Altitude Air Shower Observatory (LHAASO) is still being defined. It is envisioned to spread over an area of one square kilometer and to be located at the Yanbajing (YBJ) cosmic ray observatory in Tibet, China, which is about 4300 m above sea level. It is worth noting that YBJ now hosts two on-going experiments, *Tibet AS*γ and *ARGO*. Therefore, excellent infrastructure is already in place for *LHAASO*. Since the project is still evolving, the ultimate sensitivity of *LHAASO* is not known at the present time. There are also plans to incorporate Cherenkov telescopes into the observatory, making it a wide-field and narrow-field combo, very much like, e.g., *RXTE* and *Swift*, for X-ray astronomy.

Lessons from the success of X-ray astronomy show the importance of parallel development of narrow-field imaging and wide-field surveying experiments. The two are complementary both in technique (see Sect. 1.1) and in scientific capabilities. Narrow-field imaging experiments enable detailed studies of TeV gamma-ray sources, while wide-field surveying experiments focus mainly on discovering new sources and thus point the way for deep observations with narrow-field experiments. In particular, the latter are most effective in catching transient phenomena that could be associated with supernova or hypernova explosions, merging of neutron stars, nova outbursts, blazar outbursts, evaporation of primordial black holes, or processes that have not even been thought of yet. Rapid extragalactic transient gamma-ray signals have been used as probes into some of the most fundamental questions in physics, such as violation of Lorentz invariance. Wide-field surveying experiments can also more easily facili-

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[1] See *http://hawc.umd.edu/*

tate multi-wavelength observations, which have proven to be critical to understanding the processes of particle acceleration and radiation production in astronomical environments.

Compared to space-based experiments (such as *Fermi*), ground-based experiments are easily serviceable and can thus potentially run for a long time. This is important for studies that require high statistical precision (as well as a large sample of sources), such as dark matter searches. Ground-based experiments can also be upgraded to improve sensitivity. As long as systematic uncertainties can be controlled at a sufficiently low level, a wide-field experiment like *LHAASO* has the potential of being an effective pathfinder for the next-generation narrow-field imaging experiments (such as CTA or AGIS). This also represents an excellent opportunity for China to become a major player in the young but exciting field of TeV gamma-ray astronomy. To fully explore the promise of wide-field surveying experiments, it would be ideal to have two observatories in the northern and southern hemispheres, respectively, to cover the whole sky. This is certainly another area where international cooperation and collaboration would be critical.

The history of astronomy is full of examples that illustrate how new observational capabilities bring about new discoveries. Even in a branch as mature as radio astronomy, new transient phenomena are still being discovered. For instance, the recent discovery of rotating radio transients (RRATs) shows the presence of an intriguing population of radio pulsars that reveal themselves only in sporadic, ultra-short radio pulses (which last for milliseconds). In optical astronomy, the Sloan Digital Sky Survey (SDSS) has, in many way, changed the way that research is done. There is no pause in the effort. Many new survey experiments are being implemented or proposed, including the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS), the Dark Energy Survey (DES), and the Large Synoptic Survey Telescope (LSST), and they promise to revolutionize the field. At higher energies, the *EGRET* survey marked the beginning of GeV gamma-ray astronomy, which is being further advanced by *Fermi*. We should not expect TeV gamma-ray astronomy to be any different – a strong effort in developing sensitive survey experiments is required to push the field to the next level.

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References

Abdo, A. A., et al. 2007, ApJ, 658, L33
Abdo, A. A., et al. 2009a, ApJ, 696, 1084
Abdo, A. A., et al. 2009b, ApJ, in press (arXiv:0902.1340)
Acciari, V. A., et al. (VERITAS Collaboration) 2008a, ApJ, 684, L73
Acciari, V. A., et al. (VERITAS Collaboration) 2008b, ApJ, 679, 397
Acciari, V. A., et al. (VERITAS Collaboration) 2008c, ApJ, 679, 1427
Acciari, V. A., et al. (VERITAS Collaboration) 2009a, ApJ, 693, L104
Acciari, V. A., et al. (VERITAS Collaboration) 2009b, ApJ, submitted
Aharonian, F. 2000, New Astronomy, 5, 377
Aharonian, F., et al. 2002, A&A, 393, L37
Aharonian, F., et al. 2003, A&A, 403, L1
Aharonian, F., et al. (HESS Collaboration) 2004a, Nature, 432, 75
Aharonian, F., et al. (HESS Collaboration) 2004b, A&A, 425, L13
Aharonian, F., et al. (HESS Collaboration) 2005a, A&A, 432, L25
Aharonian, F., et al. (HESS Collaboration) 2005b, A&A, 435, L17
Aharonian, F., et al. (HESS Collaboration) 2005c, Science, 307, 1938
Aharonian, F., et al. (HESS Collaboration) 2005d, A&A, 442, L25
Aharonian, F., et al. (HESS Collaboration) 2005e, A&A, 442, 1
Aharonian, F., et al. (HESS Collaboration) 2005f, A&A, 442, 895

Aharonian, F., et al. (HESS Collaboration) 2005g, Science, 309, 746
Aharonian, F., et al. (HESS Collaboration) 2005h, A&A, 431, 197
Aharonian, F., et al. (HESS Collaboration) 2006a, A&A, 448, L43
Aharonian, F., et al. (HESS Collaboration) 2006b, A&A, 449, 223
Aharonian, F., et al. (HESS Collaboration) 2006c, ApJ, 636, 777
Aharonian, F., et al. (HESS Collaboration) 2006d, Nature, 439, 695
Aharonian, F., et al. (HESS Collaboration) 2006e, Nature, 440, 1018
Aharonian, F., et al. (HESS Collaboration) 2006f, A&A, 456, 245
Aharonian, F., et al. (HESS Collaboration) 2006g, A&A, 460, 743
Aharonian, F., et al. (HESS Collaboration) 2006h, Science, 314, 1424
Aharonian, F., et al. (HESS Collaboration) 2006i, A&A, 460, 365
Aharonian, F., et al. (HESS Collaboration) 2007a, A&A, 449, 223
Aharonian, F., et al. (HESS Collaboration) 2007b, ApJ, 664, L71
Aharonian, F., et al. (HESS Collaboration) 2007c, A&A, 473, L25
Aharonian, F., et al. (HESS Collaboration) 2007d, A&A, 475, L9
Aharonian, F., Buckley, J., Kifune, T., & Sinnis, G. 2008, Rep. Prog. Phys., 71, 096901
Aharonian, F., et al. (HESS Collaboration) 2009, ApJ, 965, L40
Albert, J., et al. (MAGIC Collaboration) 2006a, Science, 312, 1771
Albert, J., et al. (MAGIC Collaboration) 2006b, ApJ, 641, L9
Albert, J., et al. (MAGIC Collaboration) 2007, ApJ, 669, 862
Albert, J., et al. (MAGIC Collaboration) 2008a, ApJ, 685, L23
Albert, J., et al. (MAGIC Collaboration) 2008b, ApJ, 675, L25
Albert, J., et al. (MAGIC Collaboration) 2008c, ApJ, 679, 428
Aliu, E., et al. (MAGIC Collaboration) 2008, Science, 322, 1221
Albert, J., et al. (MAGIC Collaboration) 2009, ApJ, 693, 303
Aliu, E., et al. (MAGIC Collaboration) 2009, ApJ, 697, 1299
Amenomori, M., et al. 2006, Science, 314, 439
Atkins, R., et al. 2004, ApJ, 608, 680
Atkins, R., et al. 2005, ApJ, 630, 996
Bai, J. M., & Lee, M. G. 2001, ApJ, 549, L173
Beall, J. H., & Bednarek, W. 1999, ApJ, 510, 188
Begelman, M. C., Fabian, A. C., & Rees, M. J. 2008, MNRAS, 384, L19
Berezinsky, V., Bottino, A., & Mignola, G. 1994, Phys. Lett., B325, 136
Bergstrom, L., Ullio, P., & Buckley, J. H. 1998, Astropart. Phys., 9, 137
Bergstrom, L., Edsjo, J., & Ullio, P. 2001, Phys. Rev. Lett., 87, 251301
Błażejowski, M., et al. (VERITAS Collaboration) 2005, ApJ, 630, 130
Bloom, S. D., & Marscher, A. P. 1996, ApJ, 461, 657
Böttcher, M., et al. 1997, A&A, 324, 395
Böttcher, M. 2005, ApJ, 621, 176
Brogan, C. L., et al. 2005, ApJ, 629, L105
Casares, J., et al. 2005a, MNRAS, 360, 1091
Casares, J., et al. 2005b, MNRAS, 364, 899
Cesarini, A., et al. 2004, Astropart. Phys., 21, 267
Chang, C., Konopelko, A., & Cui, W. 2008, ApJ, 682, 1177
Cui, W. 2004, ApJ, 605, 662
Cui, W. 2005, Science, 309, 714
Cui, W. 2006, in Proceedings of The Vulcano Workshop on “Frontier Objects in Astrophysics and Particle Physics”, eds. F. Giovannelli, & G. Mannocchi, Italian Physical Society, Editrice Compositori, 93, 207 (astro-ph/0608042)
Cui, W., & Konopelko, A. 2007, ApJ, 665, L83
Dar, A., & Laor, A. 1997, ApJ, 478, L5
Dermer, C. D., et al. 1992, A&A, 256, L27
Errando, M., et al. (MAGIC Collaboration) 2008, in Proceedings of the 4th Heidelberg International Symposium on High Energy Gamma-Ray Astronomy, AIP Conf. Proc., 1085, 423 (arXiv:0901.3275)

Gaidos, J. A., et al. 1996, Nature, 383, 319
Ginsburg, V. L., & Syrovatskii, S. I. 1964, in The Origin of Cosmic Rays (New York: Pergamon Press)
Ghisellini, G., Tavecchio, F., & Chiaberg, M. 2005, A&A, 432, 401
Gilmore, G., et al. 2008, ApJ, 663, 948
Gregory, P. C. 2002, ApJ, 575, 427
Hooper, D., & Dingus, B. L. 2004, Phys. Rev. D, 70, 113007
Horns, D. 2005, Phys. Lett., B607, 225 (Erratum: B611, 297)
Horns, D., et al. 2007, A&A, 469, L17
Horan, D., et al. (VERITAS Collaboration) 2007, ApJ, 655, 396
Horan, D., et al. (VERITAS Collaboration) 2009, ApJ, 695, 596
Kawachi, A., et al. 2004, ApJ, 607, 949
Khangulyan, D., Aharonian, F., & Bosch-Ramon, V. 2008, MNRAS, 383, 467
Knödlseder, J. 2000, A&A, 360, 539
Konopelko, A., et al. 2003, ApJ, 597, 851
Konopelko, A., et al. (VERITAS Collaboration) 2007, Apj, 658, 1062
Kosack, K., et al. (VERITAS Collaboration) 2004, ApJ, 608, L97
Krawczynski, H., et al. 2004, ApJ, 601, 151.
Krennrich, F., et al. 2002, ApJ, 575, L9
Lenain J.-P., Boisson C., Sol H., Katarzyński K., 2008, A&A, 478, 111
Levinson, A. 2007, ApJ, 671, L29
Lyutikov, M. 2003, New Astr. Rev. 47, 513
Mannheim, K., & Biermann, P. L. 1992, A&A, 253, L21
Maraschi, L., Ghisellini, G., & Celotti, A. 1992, ApJ, 397, L5
Martí, J., Paredes, J. M., & Ribó, M. 1998, A&A, 338, L71
Mastichiadis, A., & Kirk, J. G. 1997, A&A, 320, 19
Motch, C., et al. 1997, A&A, 323, 853
Mücke, A., et al. 2003, Astropart. Phys., 18, 593
Paredes, J. M., Martí, J., Ribó, M., & Massi, M. 2000, Science, 288, 2340
Pohl, M., & Schlickeiser, R. 2000, A&A, 354, 39
Protheroe, R. J., Donea, A.-C., & Reimer, A. 2003, Astropart. Phys., 19, 559
Rees, M. J. 1978, MNRAS, 184, 61
Ribó, M., Reig, P., Martí, J., & Paredes, J. M. 1999, A&A, 347, 518
Sierpowska-Bartosik, A., & Torres, D. F. 2009a, ApJ, 693, 1462
Sierpowska-Bartosik, A., & Torres, D. F. 2009b, Astroparticle Physics, in press (arXiv:0801.3427)
Sikora, M., et al. 1994, ApJ, 421, 153
Spada, M., et al. 2001, MNRAS, 325, 1559
Stawarz, L., et al. 2006, MNRAS, 370, 981
Tanaka, T., et al. 2008, ApJ, 685, 988
Tavecchio, F., & Ghisellini, G. 2008, MNRAS, 385, L98
Tian, W., Leahy, D. A., Haverkorn, M., & Jiang, B. 2008, ApJ, 679, L85
Torres, D. F., Domingo-Santamaria, E., & Romero, G. E. 2004, ApJ, 601, L75
Tsuchiya, K., et al. 2004, ApJ, 606, L115
Uchiyama, Y., et al. 2007, Nature, 449, 576
Urry, C. M., & Padovani, P. 1995, PASP, 107, 803
Wang, Q. D., Lu, F. J., & Gotthelf, E. V. 2006, MNRAS, 367, 937
Weekes, T. C., et al. 1989, ApJ, 342, 379
White, R., & Chen, W. 1992, ApJ, 387, L81
Wood, M., et al. (VERITAS Collaboration) 2008, ApJ, 678, 594
Xue, Y. Q., & Cui, W. 2005, ApJ, 622, 160
Xue, Y. Q., Yuan, F., & Cui, W. 2006, ApJ, 647, 194