

THE TeV GAMMA-RAY MILKY WAY

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ABSTRACT

This review summarises the current status of the Galactic TeV (10^{12} eV) gamma-ray source population. It also briefly looks at the future beyond the current generation of TeV gamma-ray facilities, and highlights the role of the interstellar medium (ISM) in helping to resolve some of the challenges in interpreting the wealth of results which have been found in recent years.

Key words: Milky Way: Gamma ray

1. INTRODUCTION

The past decade has seen TeV (10^{12} eV) gamma-ray astronomy rapidly maturing as a new way to view the high energy Universe, through the great success of ground-based facilities such as HESS¹, VERITAS², MAGIC³, and MILAGRO (Abdo et al., 2007). Surveys (e.g. Aharonian et al. (2006a); Abdo et al. (2007); Aliu E. et al. (2013)) and other dedicated observations have revealed nearly 100 TeV sources located within our galaxy.

The Galactic TeV sources can be categorised based on their morphology and/or spatial/temporal correspondence with counterparts at lower energies (in particular in the radio and X-ray bands). Many are associated with specific phases in the life and death of massive stars. A major mystery, however, is that a large fraction of the Galactic sources remain unidentified due to their detection solely in the GeV to TeV gamma-ray band.

A further challenge is to understand the nature of the processes responsible for the TeV gamma-ray emission. TeV gamma-rays can reveal the presence of multi-TeV electrons and/or cosmic-rays (protons, He nuclei etc.), and hence the location of charged particle acceleration and/or interactions in our galaxy. Discrimination of electron-induced (leptonic) vs. cosmic-ray-induced (hadronic) gamma-ray emission is a key task here. This requires the sampling of energy spectra and morphologies across several bands of the electromagnetic spectrum (radio, X-rays, GeV to TeV gamma-rays). In this context, the interstellar (ISM) medium can play a vital role in the discrimination process.

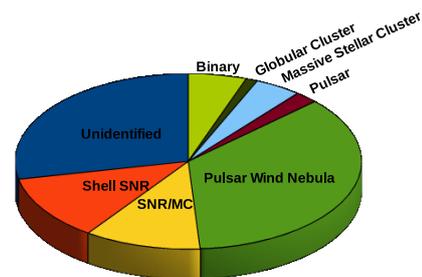


Figure 1. The Galactic TeV source population using classifications from TeVCaT.

2. THE GALACTIC TeV GAMMA-RAY SOURCE POPULATION

Figure 1 shows the type breakdown of the 92 Galactic TeV gamma-ray sources as of October 2014 according to the online catalogue TeVCaT⁴. The identified source types fall into the following categories: shell-type supernova remnants (Shell SNR), SNRs interacting with adjacent molecular clouds (Shell/MC), pulsar wind nebulae (PWNe), pulsars (ie. pulsed TeV emission from within the pulsar's magnetosphere), binary systems with a compact remnant (neutron star or black hole), massive stellar clusters, and a globular cluster. Their TeV luminosities predominantly fall into the 10^{32} to 10^{35} erg/s range.

Shell SNR There are now seven TeV shell SNRs identified – RXJ1713.7–3946, RXJ0852–4622 (Vela Jnr), RCW 86, SN 1006, Tycho, Cas A, HESS J1731–374 (see review by Rieger et al. (2013)). The last example, HESS J1731–374, is the first shell SNR to be discovered in TeV gamma-rays. The others were identified through the morphological match of their TeV emission to very similar structures in radio and/or X-rays previ-

¹ <http://www.mpi-hd.mpg.de/hfm/HESS/HESS.html>.

² <http://veritas.sao.arizona.edu/>.

³ <http://hegra1.mppmu.mpg.de/MAGICWeb/>.

⁴ <http://tevcat.uchicago.edu/>.

ously observed.

Establishing a population of TeV gamma-ray shell SNRs is a major driver of this field (Drury et al., 1994), given the long-held understanding that shell SNRs can provide the energy for the Galactic cosmic-rays (e.g. Baade & Zwicky (1934)). The subsequent success in applying diffusive shock acceleration (DSA) theory (e.g. Drury (1983); Bell (2004)) to shell SNRs provided further impetus for their study. The TeV shell SNRs are relatively young (less than a few 1000 years) and so are still accelerating particles at their fast rim shocks with typical speeds over 1000 km/s and amplified magnetic fields reaching $B \sim 100\mu\text{G}$. There is no unambiguous preference at present for a leptonic or hadronic origin of the TeV emission in shell SNRs, although the presence of non-thermal X-ray synchrotron emission provides insight into the population of accelerated electrons. However, recent assessments of the ISM towards TeV Shell SNRs may offer further insights.

Shell/MC This class of TeV shell SNRs are mature (more than 10^4 yrs), and tend to exhibit some interaction with adjacent molecular clouds (MCs). The prime examples are W28 and IC443 (Aharonian et al., 2008; Albert et al., 2007a). The fact that their TeV emission generally spatially overlaps the molecular gas, plus the lack of accompanying non-thermal X-ray emission (i.e. absence of multi-TeV electrons) suggests this class of TeV SNRs represents the most compelling evidence for cosmic-ray acceleration from SNRs. The π^0 decay signature of cosmic-ray/ISM interactions recently seen in the GeV gamma-ray spectra measured by *Fermi*-LAT towards W44 and IC443 (Ackermann et al., 2013) is further convincing evidence of this. The GeV to TeV emission is generally explained as arising from cosmic-rays diffusing out from the SNR bubble and then interacting with the adjacent gas.

PWNe The pulsar wind nebulae represent the most populous Galactic TeV source type with some notably bright examples being the Crab Nebula, Vela-X and HESSJ1825–137. Their identification is usually made based on the presence of a pulsar with known timing and spin-down power properties, and morphological comparisons in the TeV gamma-ray and X-ray bands. Based on energy spectral measurements, accelerated electrons from the pulsar wind are strongly favoured as the source of this emission, leading to TeV gamma-rays via the inverse-Compton (IC) process and X-rays via the synchrotron process. Further observational evidence in favour of electrons comes from the TeV gamma-ray spectral softening with distance from the powering pulsar seen in two examples so far – HESS J1825–137 and HESS J1303–631 (Aharonian et al., 2006b; Abramowski et al., 2012). This is consistent with electron cooling via synchrotron and IC losses. A hadronic component to the TeV emission in PWNe has been considered (e.g. Atoyan & Aharonian (1996); Bednarek & Protheroe (1997); Amato et al. (2003); Horns et al. (2006)) based on the theoretical expectation that pulsar

winds could also contain ions and the fleeting evidence for them (e.g. Gunn & Ostriker (1969); Gallant & Arons (1994); Gaensler et al. (2002)).

Given the large number of TeV PWNe, population-derived trends can be determined. The TeV PWNe tend to be associated with the younger, higher spin-down power pulsars, although as the pulsar ages, a higher proportion of luminosity appears in the TeV gamma-ray band compared to X-rays (see e.g. Kargaltsev et al. (2013)). This trend is attributed to the decay of the magnetic field with time, which leads to a higher fraction of an electron’s energy going into the IC process at the expense of synchrotron emission.

Pulsars About 150 pulsars have been seen in the GeV gamma-ray band (Abdo et al., 2013). The pulsed emission is generally attributed to curvature radiation from electrons accelerated within the pulsar’s magnetosphere. The GeV flux energy spectra typically follow a power-law with a super-exponential cutoff of the form $E^{-\Gamma} \exp[-(E/E_o)^b]$ with $b \leq 1$, spectral index Γ , and cutoff energy $E_o \sim 1 - 20$ GeV. At TeV energies, just two pulsars have been seen – the Crab Nebula (Aleksic et al., 2012; Aliu E. et al., 2011), and the Vela Pulsar⁵. The steep exponential cutoff strongly reduces the flux into the TeV band, but the detection of pulsed gamma-rays at TeV energies from the Crab has constrained the emission region to the outer magnetosphere. The pulsed TeV emission also extends to energies beyond 100 GeV, challenging current models for pulsed gamma-rays (Buehler & Blandford, 2014).

Binaries A total of five binary systems are currently identified in TeV gamma-rays – LS 5039, PSRB 1259–631, LSI+61°303, HESS J0632+057 and HESS J1018–589 (see e.g. review by Dubus (2013)). They were identified through their flux variability, which may be modulated by the orbital period of the binary system. Such systems are assumed to comprise a compact object in orbit around a massive companion O or B type star. This modulation occurs due to the strong angle dependency in the electron-positron pair conversion of TeV gamma-rays on the optical/UV photons from the massive companion, which leads to a gamma-pair cascade and hence reduction in the gamma-ray photon’s energy. A leptonic IC mechanism is invoked for the TeV emission but hadronic models are not yet ruled out. A single, but marginal TeV flare from Cyg X-1 (a black hole X-ray binary) was also seen to coincide somewhat with an X-ray flare (Albert et al., 2007b) but this has not been repeated.

Massive Stellar Clusters A number of TeV sources are associated with massive stellar clusters with a few prominent examples being HESS J1646–458 (Westerlund1), HESS J1023-575 (Westerlund2), HESS J1848–018 (W43) and TeV J2032+4130 (Cygnus OB2). Such massive clusters of B, O and

⁵<http://www.mpi-hd.mpg.de/hfm/HESS/201406-TeVPA-Amsterdam-nofilm.pdf>.

even Wolf-Rayet stars contain wind energetics (approaching 10^{39} erg/s) which are several orders of magnitude above the observed TeV luminosities. Particles may be accelerated in the wind-wind collisions of massive binary systems and/or the collective effects of the all the stellar winds combined (e.g. Reimer et al. (2006); Parizot et al. (2004)), to provide leptonic and/or hadronic TeV gamma-rays. However, the possibility of accompanying SNRs and PWNe as expected in massive clusters may also contribute to or in fact dominate the TeV emission in some cases.

Globular Clusters Terzan 5 represents the sole TeV gamma-ray globular cluster to date (Abramowski et al., 2011). The TeV emission is likely related to the large number of millisecond pulsars found in globular clusters. Interestingly, the TeV emission is slightly offset from the optical core of the cluster. This may be due to the complex mixing of winds from millisecond pulsars and massive stars with ambient and surrounding gas (e.g. Bednarek & Sobczak (2014)).

Unidentified About 30% of the Galactic TeV sources remain unidentified, due to the lack of any plausible counterpart at lower energies. Most of the Galactic TeV sources have a GeV counterpart, but the somewhat poorer angular resolution of *Fermi*-LAT compared to TeV instruments presents difficulties in comparing to radio and X-ray measurements. Nevertheless the GeV-TeV spectral comparisons have enabled insight into the leptonic vs. hadronic nature of the accelerated particles and helped to broadly discriminate PWNe vs. SNR origin in some cases. Some of these unidentified sources have been linked to massive star clusters and star formation regions (e.g. Eger et al. (2011)), hyper-energetic supernova remnants (or gamma-ray bursts in our galaxy) (Ioka & Mezaros, 2010), evolved supernova remnants (Yamazaki et al., 2006) or ancient PWNe (Tanaka et al., 2010).

3. FUTURE TeV GAMMA-RAY OUTLOOK

The HESS collaboration has recently commissioned a 28 m diameter fifth telescope which will push their energy threshold below 50 GeV. This will open up new horizons for southern hemisphere studies of pulsars (e.g. the Vela Pulsar detection), X-ray binaries, transients, as well as improving the overall sensitivity of the the full (now five-telescope) array at energies above 0.1 TeV. The major next generation facility in TeV astronomy is the Cherenkov Telescope Array (CTA)⁶, which will be about 10 times more sensitive than HESS and other current instruments and cover an expanded range of gamma-ray energies from below 30 GeV to over 100 TeV. CTA will comprise arrays of about 10 telescopes in the Northern hemisphere, and up to about 70 telescopes in the Southern hemisphere. Construction is expected to commence by about 2015 and full completion of the arrays (north and south) is expected around 2020.

CTA will provide TeV gamma-ray imaging approaching 1 arc-minutes in resolution (68% containment radius), about 5 times better than HESS currently achieves. In terms of Galactic astronomy, CTA is expected to detect sources out to the edge of the spiral arms, providing the first Galactic census of multi-TeV particle accelerators. Many of the science questions that CTA will address are discussed in a special edition (v43) of the *Astroparticle Physics journal*⁷. The High Energy Water Cherenkov (HAWC)⁸ telescope considerably improves on the water Cherenkov detection method pioneered by Milagro. HAWC's 24 hr operation and hemispheric field of view (quite complementary to CTA) will enable it lead the way in the studies of TeV transients and very extended gamma-ray sources at these energies.

4. ROLE OF THE ISM IN UNDERSTANDING TeV GAMMA-RAY EMISSION

The ISM is a strong target for cosmic-ray collisions, and moreover, it has a major impact on the propagation of cosmic-rays and electrons to influence the morphology and energy spectra of hadronic and leptonic gamma-ray sources. Cosmic-ray/ISM collisions are expected to yield a spatial match between the TeV gamma-ray and ISM distributions, providing a smoking gun signature to trace the origin of Galactic cosmic-rays. Furthermore, the energy dependent and directional diffusion of cosmic-rays through the ISM and into dense molecular cloud cores will give rise to specific spectral shapes and morphologies across the GeV to TeV bands (Aharonian & Atoyan, 1996; Gabici et al., 2007, 2009).

Such diffusive effects have been used to explain the GeV to TeV gamma-ray spectral shapes from several mature SNR/MC sources (e.g. Nava & Gabici (2013)), and the diffuse TeV emission towards the inner few 100 pc of our galaxy (Aharonian et al., 2006). Recent assessments of the combined atomic and molecular ISM towards young TeV Shell SNRs (Fukui et al., 2012; Fukuda et al., 2014) offer observational evidence for a hadronic component. This is a key step towards establishing young SNRs as Galactic cosmic-ray accelerators. Finally, molecular clouds usually found adjacent to PWNe may also offer the chance to probe for protons in pulsar winds, or, cosmic-rays from the accompanying SNR (Voisin et al., 2014).

These TeV/ISM comparisons have made extensive use of surveys in the CO line (Dame et al., 2001; Onishi et al., 2012) and the HI atomic line (McClure-Griffiths et al., 2005) which have resolutions well-matched to or slightly better than that of current TeV instruments. CTA's sensitivity is expected to reveal the more diffuse TeV emission surrounding many sources, for example from cosmic-rays escaping SNRs (Malkov et al., 2013; Nava & Gabici, 2013; Acero et al., 2013), and cosmic-rays entering dense cores of molecular clouds (Nicholas et al., 2012). Hence, improved arc-minute resolution Galactic plane surveys in CO (Burton et al.,

⁶ <https://www.cta-observatory.org/>.

⁷ APh (2013) vol. 43.

⁸ www.hawc-observatory.org/.

2013; Braiding et al., 2014), and mapping of TeV sources in dense gas tracers such as CS and NH₃ (Nicholas et al., 2012; Maxted et al., 2012; Voisin et al., 2014) such as those provided by the Mopra telescope will also be necessary to perform the next stage of TeV/ISM comparisons that CTA will provide in the coming years.

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