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Memorie della

(V)HE γ-ray emission from supernova remnants

(and star forming regions)

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Abstract. I review the current status of high-energy (HE or "GeV") and very-high-energy (VHE or "TeV") γ-ray observations of supernova remnants (SNRs), and discuss implications for the widely accepted hypothesis that these objects are the sources of Galactic cosmic rays (GCRs). Several young and middle-aged SNRs have now been detected by *Fermi*-LAT in the GeV γ-ray regime, and by HESS, MAGIC or VERITAS in the TeV regime. Ambiguities remain in many of these objects as to whether the observed emission is predominantly leptonic or hadronic in origin. In those SNRs for which a hadronic origin seems preferred, the observed spectrum generally differs from the simplest expectations of non-linear diffusive shock acceleration theory. Star-forming regions and possible collective acceleration mechanisms in the accompanying superbubbles have been discussed as alternative sources for GCRs, and I briefly discuss γ-ray observations of such objects.

Key words. Gamma rays: observations – Radiation mechanisms: nonthermal – Supernova remnants – Cosmic rays – Open clusters and associations: general

1. Introduction

1.1. GeV and TeV γ-rays

High-energy (HE) or "GeV" γ-rays, with energies in the approximate range 0.1–100 GeV, are detected by space experiments such as the former CGRO-EGRET and currently *Fermi*-LAT. The highest detectable γ-ray energy with such instruments is limited by the calorimeter depth and collecting area possible on a satellite.

Very-high-energy (VHE) or "TeV" γ-rays, with energies in the approximate range 0.1–100 TeV, are detected using the Earth's atmosphere as calorimeter. The currently most sensitive detectors are imaging atmospheric Cherenkov telescope (IACT) arrays, including *HESS* (located in Namibia), *MAGIC* (Canary Islands) and *VERITAS* (Arizona).

1.2. Galactic cosmic rays and SNRs

Charged cosmic rays with energies above ~1 GeV, and up to the "ankle" at $\sim 3 \times 10^{18}$ eV, are thought to be Galactic in origin. While direct measurements are available only in the heliosphere, diffuse γ-ray emission indirectly demonstrates that these Galactic cosmic rays (GCRs) do permeate the Galaxy, but that their density is less in the Large Magellanic Cloud and even lower in the Small Magellanic Cloud, conforming to a proportionality with star formation rate. It is generally agreed that the sources of GCRs must be able to acceler-

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ate protons up to the energy of the observed "knee" in their energy spectrum at ~3×10^{15} eV.

Supernova remnants (SNRs) are widely considered likely sources of GCRs up to the knee, for several reasons. A well-studied particle acceleration mechanism, diffusive shock acceleration (or first-order Fermi acceleration), is thought to operate at SNR shocks; the composition of GCRs appears compatible with an origin in SNRs; and the energy available in SNRs is such that the conversion of ~10% into GCRs would be sufficient to maintain their Galactic density at the observed level.

X-ray observations provide evidence for efficient *electron* acceleration at the shocks of relatively young SNRs through synchrotron emission. There is also indirect evidence for efficient proton and heavier ion acceleration in the form of modified hydrodynamics and magnetic field amplification, as expected from non-linear diffusive shock acceleration theory (e.g. Caprioli et al. 2010, and references therein).

1.3. Hadronic vs. leptonic γ-ray emission

Direct evidence for proton and heavier ion acceleration in SNRs can be obtained by detecting γ-rays resulting from **hadronic** interactions. This has been one of the historical aims of TeV γ-ray astronomy (Drury et al. 1994). Accelerated (CR) protons or ions interact with protons or ions from the interstellar or circumstellar medium (ISM/CSM), producing charged and neutral pions; the neutral pions decay into two γ-rays, which can be observed.

As the relevant interaction cross-section is approximately energy-independent, the observed γ-ray spectral index Γ directly reflects that of the underlying proton spectrum (at a proton energy an order of magnitude higher than that of the observed γ-ray). The γ-ray luminosity L_γ is proportional to $\int n_{\rm CR}\, n_{\rm ISM}\, dV$, where $n_{\rm CR}$ and $n_{\rm ISM}$ denote the accelerated and ambient proton densities; if one of these densities can be approximated as uniform, we have:

$$L_\gamma \propto E_{\rm CR} n_{\rm ISM} \quad (\text{if } n_{\rm ISM} \text{ uniform}) \qquad (1)$$

$$\propto n_{\rm CR} M_{\rm cloud} \quad (\text{if } n_{\rm CR} \text{ uniform}) \qquad (2)$$

Here $E_{\rm CR}$ represents the total energy in accelerated hadrons (in the case where the ambient medium is homogeneous), while $M_{\rm cloud}$ is the total mass of interstellar cloud permeated by cosmic rays (in the case where the emission predominantly originates in dense clouds, see section 4). In the hadronic case, the γ-ray morphology is thus expected to correlate with both the accelerated and ambient proton densities.

The main difficulty in unambiguously detecting the expected hadronic signal from SNRs is discriminating between this and competing **leptonic** emission processes. The main leptonic process is inverse Compton (IC) emission, in which an accelerated electron interacts with a low-energy ambient photon to yield a γ-ray. The dominant ambient ("target") photon contributions are from the cosmic microwave background and the diffuse infrared Galactic background. As these are essentially uniform on the scale of the SNR, the leptonic γ-ray morphology (in contrast to the hadronic case) correlates solely with the density of accelerated electrons (unless there is a significant local source of target photons, e.g. from dust in a nearby molecular cloud).

When the high-energy electron population responsible for the IC emission is also observed in (typically X-ray) synchrotron emission, the combination in principle allows inference of the value of the magnetic field B (in a simplified, one-zone model). Detailed interpretation of leptonic emission from SNRs is however complicated by the expected non-uniformity of B, as well as by uncertainties in the local target photon density.

2. Young, "historical" SNRs

2.1. Cas A

Cassiopeia A is the next-to-youngest SNR known in the Galaxy (after G 1.9+0.3), with an age of ~300 yr; it will be treated as a "historical" SNR, despite the lack of clear evidence for historical observations of the supernova itself. Its initial detection in TeV γ-rays by HEGRA was subsequently confirmed and refined by MAGIC and VERITAS; it has more recently been detected in GeV γ-rays by *Fermi*-LAT (Abdo et al. 2010a, and references therein).

While Cas A does exhibit non-thermal X-ray emission, evidence for strong (~mG) magnetic fields disfavours a leptonic origin for its γ-ray emission. The combined γ-ray spectral data (see Fig. 4 of Abdo et al. 2010a) can be fit by hadronic models with either a hard spectrum ($\Gamma = 2.1$) and a proton energy cutoff at 10 TeV, or a steeper spectrum ($\Gamma = 2.3$) without a cutoff. This should be contrasted with general expectations from modern non-linear diffusive shock acceleration theory, which predicts a concave but hard proton spectrum ($\Gamma \sim 2.1$), with a cutoff which at some point in SNR evolution must reach a few times 10^{15} eV.

2.2. Tycho and Kepler

The remnant of Tycho's supernova (SN 1572) has very recently been detected in TeV γ-rays by VERITAS (Acciari et al. 2011). The detected flux corresponds to a luminosity $L_{1-10\,\mathrm{TeV}} \approx 1.3 \times 10^{33}$ erg/s at a distance of 4 kpc, and the observed spectrum is poorly constrained ($\Gamma = 2.0 \pm 0.5_{\mathrm{stat}} \pm 0.3_{\mathrm{sys}}$). The γ-ray emission centroid appears shifted NE of the SNR's center (by $2.4' \pm 1.4'_{\mathrm{stat}} \pm 0.8'_{\mathrm{sys}}$), in the direction of a possibly interacting CO cloud (and of the brightest synchrotron-emitting region).

The remnant of Kepler's supernova (SN 1604) has so far not been detected in γ-rays. The most stringent upper limit (Aharonian et al. 2008b) implies a luminosity $L_{1-10\,\mathrm{TeV}} < 2 \times 10^{33}$ erg/s at a distance of 4.8 kpc, but it should be noted that the distance uncertainty of about ± 1.5 kpc implies a factor ~2 uncertainty in luminosity.

2.3. SN 1006: bipolar morphology

In 130 hours of observations (after quality cuts), HESS detected TeV γ-ray emission from the NE and SW rims of SN 1006 (Acero et al. 2010), in a morphology well-correlated with the non-thermal X-ray emission from this SNR. An ambiguity persists as to the leptonic or hadronic origin of this γ-ray emission: an IC (one-zone) model would require a relatively low magnetic field, $B \approx 30\,\mu$G, while a hadronic scenario requires a relatively large total energy in accelerated protons and ions, and a γ-ray spectral cutoff around 10 TeV.

Irrespective of the nature of the γ-ray emitting high-energy particles (electrons or ions), the observed morphology directly reveals their spatial distribution (in contrast to the synchrotron morphology which also reflects the magnetic field distribution), as the shock is thought to expand in a nearly uniform medium. Indeed, SN 1006 is unique as the remnant of a young, type Ia supernova which occurred in the presumably little disturbed interstellar medium well above the Galactic plane.

X-ray observations show that the striking bipolar morphology seen in synchrotron is compatible with "polar caps" rather than an "equatorial band" of enhanced emission (Rothenflug et al. 2004). In the natural interpretation in which the symmetry axis is determined by the background magnetic field, this suggests that *parallel* shocks, rather than perpendicular ones, are where particle acceleration is most efficient. An observational confirmation of this magnetic geometry would be very useful, but is made complicated by the fact that the more readily inferred *post-shock* magnetic geometry is likely strongly influenced by instabilities.

3. SNRs with TeV shell morphology

3.1. Well-studied non-thermal SNRs

Although undoubtedly historical, SN 1006 can also be regarded as an example of an SNR in which a shell-type (limb-brightened) morphology is resolved in (TeV) γ-rays. The best-studied example of this class is probably RX J1713.7–3947 (also known as G 347.3–0.5), which was the first SNR shell to be resolved in TeV γ-rays (Aharonian et al. 2004). Deeper observations revealed a very good spatial correlation with the (non-thermal) X-ray emission from this shell, and large zenith angle observations allowed a precise determination of its γ-ray spectrum over more than two decades of energy (Aharonian et al. 2007a), which is well described as a power law of index $\Gamma \approx 2.0$ with an energy cutoff or break at ~10 TeV.

Another well-studied member of this class is RX J0852.0–4622 (also known as G 266.2–1.2 or "Vela Junior"), in which the TeV γ-ray morphology (Aharonian et al. 2007b) also correlates well with that in X-rays. RCW 86 (more properly known as G 315.4–2.3) can probably also be considered a member of this class, although current statistics do not significantly favour a limb-brighened γ-ray morphology (Aharonian et al. 2009). The latest member of the class is HESS J1731–347, to be discussed below. The median γ-ray luminosity of these objects is $L_{1-10\,\mathrm{TeV}} \approx 9 \times 10^{33}$ erg/s.

3.2. A new non-thermal shell

HESS J1731–347 is the most recent addition to the class of SNRs with TeV shell morphology and non-thermal X-ray emission, and the first to be discovered through γ-ray observations. This TeV γ-ray source was discovered in the HESS Galactic plane survey, and initially considered unidentified. Tian et al. (2008) subsequently found a new radio shell, G 353.6–0.7, coincident with the γ-ray source. Deeper HESS observations later exhibited significant limb-brightening in γ-rays, with a radial profile compatible with that of the radio shell, and *XMM* observations of (part of) the shell revealed rims of emission with non-thermal spectra, thereby firmly establishing HESS J1731–347 as a member of the class (Abramowski et al. 2011b, and references therein). This example suggests that the next generation TeV γ-ray observatory, CTA, should enable the discovery of many more non-thermal SNRs (see Renaud et al., these proceedings).

3.3. Young and γ-ray shell SNRs

The TeV γ-ray shell SNRs discussed here share a number of properties with the young SNRs discussed in section 2. Their X-ray emission is dominantly non-thermal (although thermal X-ray emission is also seen in RCW 86 and the historical SNRs), their radio synchrotron emission can be relatively weak, and their γ-ray luminosities $L_{1-10\,\mathrm{TeV}}$ are of order a few times 10^{33} erg/s (lower for historical SNRs and higher for TeV shells). Similar conclusions are also reached for the leptonic or hadronic interpretation of their γ-ray emission.

The *leptonic* scenario might explain the spatial correlation with X-ray synchrotron emission seen in many of these SNRs. However, the implied magnetic field values (in one-zone models) are generally fairly low, of order $10\,\mu$G, in apparent contradiction with evidence for turbulent magnetic field amplification, in particular from the sharpness of X-ray synchrotron rims. It is also difficult to reproduce the observed γ-ray spectral shapes in one-zone models.

The *hadronic* interpretation has more freedom to reproduce the γ-ray spectral shape, but all γ-ray detected SNRs show spectral indices $\Gamma > 2.0$, or energy cutoffs at $E_\gamma \sim 10$ TeV; in many cases the spectrum must flatten to $\Gamma \sim 2$ towards lower energies, otherwise the energy required in accelerated particles becomes prohibitively large. This would imply that accelerated particle spectra in all young or TeV shell SNRs have cutoffs at $E_p \sim 10^{14}$ eV or less, well short of the "knee" energy.

The hadronic scenario also offers no obvious explanation for the high spatial correlation of γ-rays with synchrotron X-rays in these SNRs, and the lack of a stronger correlation with the surrounding medium density. Moreover, in the purely non-thermal shells RX J1713.7–3947, RX J0852.0–4622 and HESS J1731–347, the hadronic interpretation requires a relatively high surrounding medium density ($n \sim 1\,\mathrm{cm}^{-3}$), in strong contrast to the upper limits on n derived from the lack of observed thermal X-ray emission, which are of a few times $0.01\,\mathrm{cm}^{-3}$ (assuming a post-shock temperature $k_\mathrm{B}T \sim$ keV).

4. SNR / molecular cloud interactions

4.1. IC 443 and W28

A different class of γ-ray emitting SNRs, in which there is ample target density for hadronic emission, are those interacting with molecular clouds (MCs). A well-studied example is IC 443, in which MAGIC discovered a compact TeV γ-ray source, later confirmed by VERITAS, coincident with a GeV γ-ray source confirmed by *Fermi*-LAT (Abdo et al. 2010b, and references therein). The γ-ray source appears to have an extent compatible with shocked molecular clouds known in IC 443, but much smaller than the whole SNR. The combined spectral data can be described with a steep spectral index, $\Gamma = 2.6 \pm 0.1$, above a break energy of about 3 GeV.

Another well-studied example is W28, in which HESS discovered a complex γ-ray morphology (Aharonian et al. 2008a). One source, HESS J1801–233, lies on the East rim of W28, coincident with a previously known GeV source and radio synchrotron hot spot; its morphology matches a molecular cloud seen in CO, and coincident maser emission confirms that the cloud is interacting with the SNR shock. Its TeV γ-ray spectrum also appears steep, with index $\Gamma = 2.7 \pm 0.3_{\rm stat} \pm 0.2_{\rm sys}$. Intriguingly, another region of TeV γ-ray emission, HESS J1800–240B, matches a CO cloud at a compatible velocity and thus distance. This could be interpreted as an example of a "passive" cloud "illuminated" by cosmic rays escaping from W28 (see Gabici, these proceedings), although the lack of significant spectral difference from HESS J1801–233 may argue against such a scenario.

4.2. General properties and discussion

Several other examples or candidates of SNRs interacting with molecular clouds coincide with TeV γ-ray sources (see Chaves; Méhault et al.; Reichardt et al., these proceedings). Such SNRs are often prominent sources in GeV γ-rays (Castro & Slane 2010; Brandt et al., these proceedings). A useful observational signature of shock interaction with a molecular cloud is provided by the 1720 MHz OH maser. A key observational issue is angular resolution in γ-rays, which is not always sufficient to discriminate between interacting clouds and other potential γ-ray sources, such as pulsar wind nebulae in composite SNRs. Specific SNRs will not be discussed further here, but some general observations can be made on the properties of the class, and their implications for cosmic-ray origin discussed.

The morphological match to a dense cloud seen in many cases makes a hadronic interpretation natural, and one might have expected such molecular clouds to act as probes of the cosmic-ray acceleration potential of SNRs. However, while the cloud masses and observed fluxes do indeed imply a large enhancement of the cosmic-ray density above the typical interstellar value, the observed spectra are much too steep to represent the source spectrum of GCRs, and flatten only below a few GeV. The steep spectra likely result from modification of the shock acceleration process or the shock structure due to propagation in the dense cloud, and thus have no direct bearing on the question of the cosmic-ray spectrum released by SNRs into the general interstellar medium.

5. Addendum: Star forming regions

5.1. SNRs vs. alternative GCR sources

The above survey may be summarised by saying that there is currently no clear evidence that an energy $\sim 3 \times 10^{15}$ eV can be attained by protons in *any* γ-ray detected SNR (at least not with the theoretically expected hard spectra with $\Gamma \sim 2$), and thus observational confirmation that SNRs can accelerate GCRs to the "knee" energy is still lacking. It may be that the "PeVatron" phase of SNRs in which this energy is reached is of very short duration, or that the "knee" is a local feature of the GCR distribution due to an untypical recent and nearby SNR. Nonetheless, the lack of direct observational evidence in favour of individual SNRs could motivate renewed consideration of alternative sources of GCRs.

Estimates of the energetics of SNRs as GCR sources often neglect the fact that the progenitors of core-collapse supernovae are not typically formed in isolation, but rather in massive star forming regions. It is thought that the energy input of stellar winds and successive supernovae in such regions combine to blow a bubble of hot gas in the interstellar medium. Up to $\sim$75% of all supernovae may occur in such "superbubbles" (Higdon & Lingenfelter

2005). It has been hypothesized that unique particle acceleration mechanisms may operate in such massive star forming regions, for instance in the (colliding) winds of massive stars (e.g. Cassé & Paul 1980) or due to turbulent and multiple shock acceleration (e.g. Parizot et al. 2004), so that superbubbles might constitute major sources of GCRs.

5.2. γ-ray observations

Westerlund 1 is the most massive stellar cluster known in the Galaxy, with a rich population ($\geq$ 24) of Wolf-Rayet stars; its total power in the form of stellar winds and expanding SNRs has been estimated as $\sim 3 \times 10^{39}$ erg/s. A very extended TeV γ-ray source coincident with this cluster has recently been detected by HESS (Ohm et al. 2010), with a relatively hard spectrum ($\Gamma = 2.2 \pm 0.1_{\mathrm{stat}} \pm 0.2_{\mathrm{sys}}$) and a total γ-ray luminosity $L_{1-10\,\mathrm{TeV}} \approx 5 \times 10^{34}$ erg/s. Given the available statistics, no significant substructure is detected within the $\sim 1^{\circ}$ extent of the source around Westerlund 1; no other plausible counterparts to the extended γ-ray emission are known in this region.

A TeV γ-ray source was also discovered by HESS coincident with the stellar cluster Westerlund 2, although the subsequent discovery of PSR J1022-5746 by *Fermi*-LAT provides an alternative scenario for the origin of at least part of the TeV γ-ray emission (Abramowski et al. 2011a, and references therein). Evidence for TeV γ-ray emission from the star cluster W49A was also recently reported by HESS (Brun et al. 2010). Other TeV γ-ray sources could be associated with stellar clusters, such as TeV J2032+4130 with Cygnus OB2, HESS J1614–518 with Pismis 22, and HESS J1848-018 with W43; *Fermi*-LAT also very recently detected GeV γ-ray emission from the latter region (Lemoine-Goumard et al., these proceedings).

5.3. Discussion

Massive star forming regions have been proposed as possible sources for GCRs. The detection of TeV γ-ray emission from the direction of several such stellar clusters, including the most massive, provides direct evidence for $\sim 10^{14}$ eV particles in those regions. However, more detailed morphological and multi-wavelength studies are necessary before the emission can be definitely ascribed to the clusters themselves, as opposed in particular to the nebulae of pulsars born in the clusters. Further studies of superbubble particle acceleration and γ-ray emission scenarios are also needed, to predict in particular the spatial and spectral distribution of accelerated particles, and to constrain the target matter and photon fields respectively for hadronic and leptonic emission processes.

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