UNDERSTANDING HADRONIC GAMMA-RAY EMISSION FROM SNRs

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We aim to test the plausibility of a theoretical framework in which the gamma-ray emission detected from supernova remnants may be of *hadronic* origin, i.e., due to the decay of neutral pions produced in nuclear collisions involving relativistic nuclei.

In particular, we investigate the effects induced by magnetic field amplification on the expected particle spectra, outlining a phenomenological scenario consistent with both the underlying Physics and the larger and larger amount of observational data provided by the present generation of gamma experiments, which seem to indicate rather steep spectra for the accelerated particles.

In addition, in order to study to study how pre-supernova winds might affect the expected emission in this class of sources, the time-dependent gamma-ray luminosity of a remnant with a massive progenitor is worked out. Solid points and limitations of the proposed scenario are finally discussed in a critical way

SNRs, COSMIC RAYS AND γ-RAYS

Supernova remnants (SNRs) are widely regarded as the sources of Galactic cosmic rays (CRs) because they are in principle able to account for the required energetics [1] and because diffusive shock acceleration (DSA) at SNR forward shocks [15-20] naturally predicts power-law spectra $\propto E^{-2}$, in decent agreement with the diffuse spectrum of Galactic CRs after propagation in the Milky Way [100].

An efficient CR acceleration is also expected to lead to γ-ray emission from SNRs due to the decay of π^0 produced in nuclear collisions between relativistic nuclei and the background gas [2]. Such a *hadronic emission* reflects the parent CR distribution in terms of spectral slope

The present generation of γ-ray telescopes, both in the GeV (Fermi, AGILE) and in the TeV (HESS, VERITAS, MAGIC,...) band is providing us with an unprecendeted wealth of data: here below we show a list of known or possible γ-ray-bright SNRs in order to understand which precious information about where and how CRs are actually accelerated can be inferred from this kind of observations.

Coordinates	SNR	Age(kyr)	α_{GeV}	α_{TeV}	Refs.
		γ-ray-bright Supernova Remnants			
6.4−0.1	W28 North	35–45	2.09±0.08	2.66±0.27	[14, 31–34]
	W28 A,B,C	35–45	2.19±0.14	2.50±0.20	[14, 31, 32]
8.7−0.1	W30	10–50	2.4±0.07	2.72±0.06	[14, 35–38]
31.9+0.0	3C 391	4	2.33±0.11		[35]
34.7−0.4	W44	15	2.06±0.03		[14, 39]
43.3−0.2	W49B	1–4	2.18±0.04	3.1±0.3	[40]
49.2−0.7	W51C	10–20	1.7±0.3		[14, 41–43]
106.3+2.7		10		2.29±0.33	[14, 34, 44]
119.5−2.1	Cas A	0.330	2.01±0.1	2.3±0.2	[14, 45–47]
120.1+1.4	Tycho	0.438	2.3±0.1	1.95±0.50	[14, 48, 49]
189.1+3.0	IC443	30	1.93±0.03	3.05±0.40	[14, 34, 43, 50–54]
205.5+0.5	Monoceros	30–150		2.53±0.26	[14, 34, 55]
266.2−1.2	Vela Jr.	0.6–4		2.24±0.04	[56, 57]
315.4+2.3	RCW 86	1.825		2.41±0.16	[58]
327.6+14.6	SN1006 NE	1.004		2.54±0.15	[59]
	SN1006 SW	1.004		2.34±0.22	[59]
347.3−0.5	RX J1713.7-3946	1.6	1.5±0.1	2.04±0.04	[4, 60–63]
348.5+0.1	CTB 37A	1.617	2.19±0.07	2.30±0.13	[14, 35, 64]
348.7+0.3	CTB 37B	2.7–4.9		2.65±0.19	[64]
349.7+0.2		2.8	2.10±0.11		[35]
353.6−0.7	HESS J1731-347	27		2.26±0.10	[65, 66]
		Other possible candidates			
0.0+0.0	SGR A East	8	∼2.2		[14, 36, 67]
12.8−0.0	HESS J1813-178	0.3–25		2.09±0.08	[36, 38]
21.5−0.9	HESS J1833-105	0.8–1		2.08±0.22	[68]
23.3−0.3	W41	60–100		2.45±0.16	[14, 36, 38, 69]
27.8+0.6		35–55			[34]
28.8+1.5		32			[34]
29.7−0.3	Kes 75	0.7–0.8		2.26±0.15	[68]
35.6−0.4	HESS J1858+020	30		2.2±0.1	[66, 70]
40.5−0.5	HESS J1908+063	20–40		2.08±0.10	[14, 68, 71]
54.1+0.3		2.9		2.3±0.3	[72]
65.1+0.6	0FGL J1954.4+2838	4–14			[38, 43, 73]
78.2+2.1	γ Cygni	5			[14, 34, 74]
119.5+10.2	CTA 1	13–17			[34]
132.7+1.3	HB3	30			[14, 34]
296.4−9.45?	HESS J1507-662	1?		2.24±0.16	[75, 76]
338.3+0.0	HESS J1640+465	20–40		2.42±0.14	[36]
343.0−0.6	RCW 114	20			[34]
359.1−0.5	HESS J1745-303	20–50	∼2.17	2.71±0.11	[14, 76, 77]

[a] W28N, IC443, W51C, W44 and W49B show evidence of a cut-off around 1–20 GeV.
[b] Ref. [14] points out SNRs in physical contact with MCs, except Tycho according to ref. [78].

Table 1. Photon spectral index α inferred in γ-ray-bright SNRs, both in the GeV and in the TeV bands. Associated systematic errors are typically in the range ±(0.1-0.2). Information about SNR nomenclature, ages, distances and associations can be found in the Green's Catalogue (http://www.mrao.cam.ac.uk/surveys/snrs/snrs.data.html) and in refs. [79–81]. See also http://tevcat.uchicago.edu and http://www.mppmu.mpg.de/~rwagner/sources/index.html for catalogues of known TeV sources.

Almost all the sources associated with SNRs show spectra steeper than E^{-2}, i.e. the standard prediction at strong shocks

GeV to TeV steep spectra are at odds with leptonic scenarios in which the γ-ray emission is due to Inverse Compton Scattering. In this case in fact $\alpha_{GeV} \simeq \alpha$-0.5, with $E^{-\alpha}$ the CR spectrum

MODELING CR ACCELERATION

In young SNRs there are several evidences of magnetic fields as large as 100-300μG, much larger than typical interstellar ones, due to plasma instabilities excited by streaming CRs [19,62,82-89,95,98].

We propose here that steep spectra are due to the fact that, in such large fields, CR feel compression ratios *r* smaller than the fluid's because of the enhanced phase velocity of their scattering centers (e.g. Alfvén waves).

$$r=\frac{u_1}{u_2}\to\tilde{r}=\frac{u_1+v_{A,1}}{u_2+v_{A,2}}$$

According to *resonant streaming instability* saturation [19], the pressure in amplified magnetic field P_B is proportional to the pressure in CRs,

$$\frac{P_B}{\rho V_{sh}^2}=\frac{B^2}{8\pi\rho V_{sh}^2}\approx\frac{\xi_{cr}}{2M_A} \qquad M_A=\frac{2}{\xi_{cr}}\frac{(1-\xi_{cr})^{5/2}}{2-\xi_{cr}}$$

where ξ_{cr} is the fraction of the bulk energy ρV_{sh}^2 channeled into CRs. We took the Alfvén velocity in the *amplified* field upstream, calculated as in ref. [99], and put $v_{A,2}=0$ downstream for isotropy.

The compression ratio actually felt by accelerated particles thus reads:

$$\tilde{r}=r\left(1-\frac{1}{M_{A,1}}\right)=\frac{\gamma_{\rm eff}+1}{\gamma_{\rm eff}-1+2/M_s^2}\left[1-\frac{\xi_{cr}(2-\xi_{cr})}{2(1-\xi_{cr})^{5/2}}\right]$$

where $\gamma_{\rm eff}=\frac{1}{3}\frac{5+3\xi_{cr}}{1+\xi_{cr}}$ is the gas+CRs *effective* adiabatical index [28].

In DSA theory the spectral slope of the accelerated particles depends only on the average compression ratio felt, which simply is:

$$\alpha=\frac{\tilde{r}+2}{\tilde{r}-1}$$

Therefore, for small Alfvénic Mach number M_A spectra may be steeper than the standard prediction E^{-2} for strong shocks with *r = 4* or for CR modified shock with even larger *r* at the highest energies.

MODELING THE SNR EVOLUTION

We focus here on a SNR with a very massive progenitor to also illustrate the possible role of pre-SN winds during the Red-Giant and the Wolf-Rayet stages. The circumstellar medium the shock propagates into hence consists of a dense and cold RG wind with power-law ρ^{-2} density profile, a hot bubble of rarefied ($n\sim0.01cm^{-3}$) and finally the odinary ISM [106-109].

The SNR evolution is accounted for from the ejecta-dominated to the Sedov stage via the analytic *thin-shell approximation* [111,112], also including the contributions of both advected (via γ_{eff}) and escaping CRs.

Simpler profiles may however investigated within this formalism by a straightforward choice of parameters as the masses going into the winds.

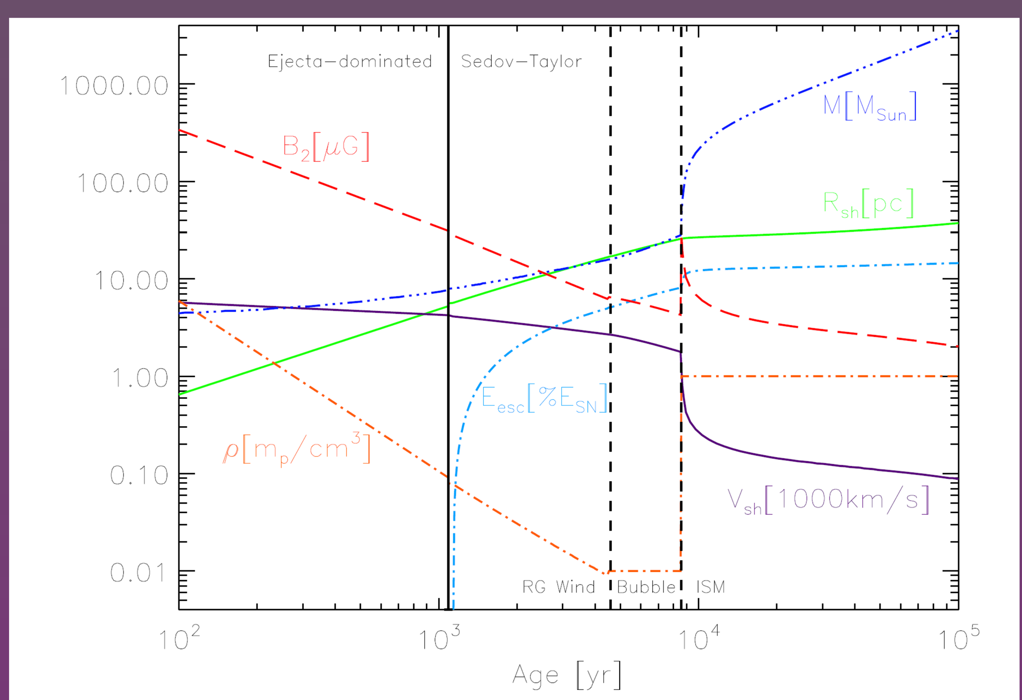

Figure 2. Time evolution of relevant physical quantities for a fixed CR acceleration efficiency ξ_{cr} = 0.1. The vertical solid line indicates the transition between ejecta-dominated and Sedov-Taylor stages, while vertical dashed lines, from left to right, mark the boundaries of wind zone, hot bubble and ISM, as in the labels (see also the description in section 3).

WHAT OBSERVATIONS SAY

We finally compare the output of our model with the slopes inferred in γ-ray-bright sources in Table 1, under the hypothesis that the emission is of hadronic origin.

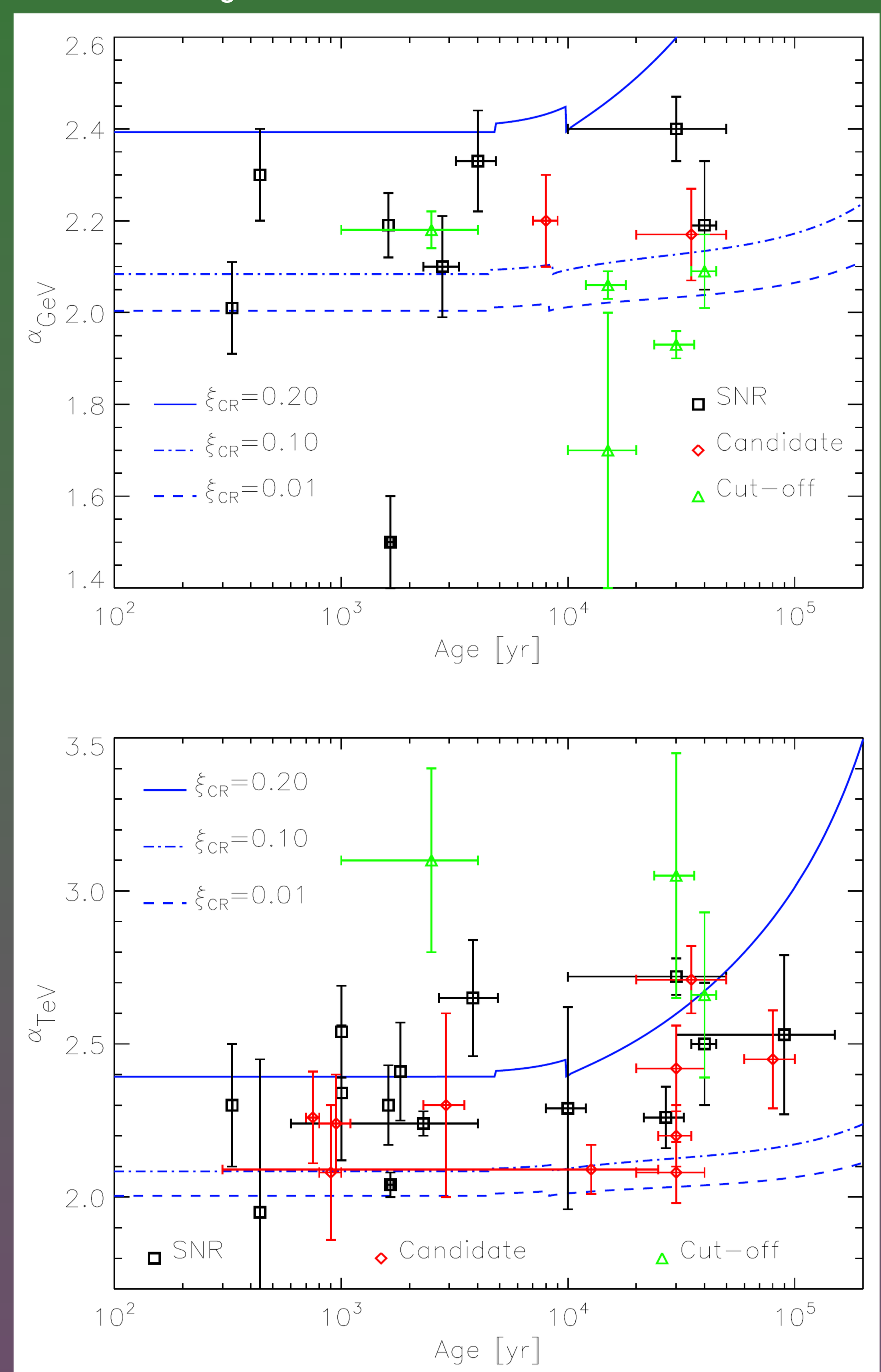

Figure 3. γ-ray-bright SNRs detected in the GeV (top panel) and in the TeV (bottom panel) band as in table 1. Different lines correspond to the CR spectral slope as a function of time, for different acceleration efficiencies as in the legend.

The inferred slopes can be reproduced by accounting for CR acceleration efficiencies as large as ξ_{cr}=0.1-0.2

The low number of γ-ray emitting SNRs with ages between about 3 and 10 kyr may be explained by the shock propagation in rearefied hot bubbles exacavated by fast pre-SN winds

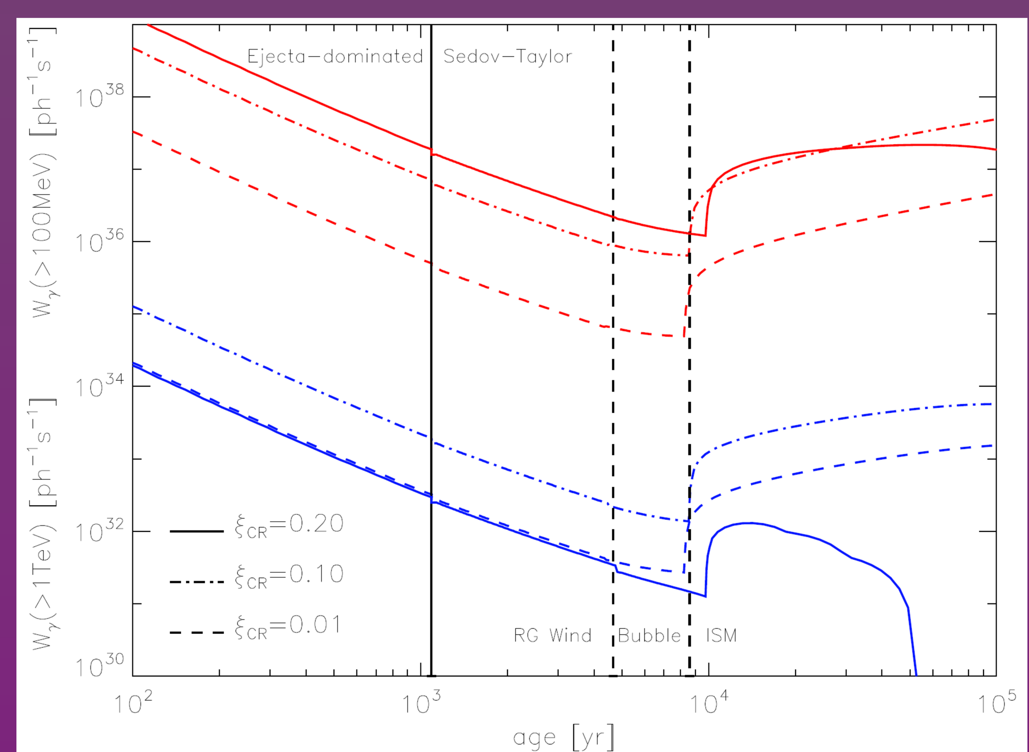

Figure 4. Time evolution of SNR γ-ray luminosity, both in the GeV (upper lines) and in the TeV band (lower lines). Solid, dashed and dot-dashed lines correspond to different CR acceleration efficiency, as in the legend. Vertical lines illustrate the evolutionary stages for the case ξ_{cr} = 0.1, as in figure 2.

CAVEATS

- Some SNRs are associated with nearby molecular clouds, which enhance the actual luminosity, but also raise theoretical issues related to the poorly known details of shock progation in partially neutral media and/or of CR diffusion around their sources.
- Magnetic field may be amplified through mechanisms other than *resonant* streaming instability (e.g. Bell's modes). We also need better (i.e. more than phenomenological) treatment of instability saturation and particle scattering in SNR environments.
- These results obtained via the presented three-fluid model have to be checked against full non-linear theory of DSA (though see [99,117]).

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