Constraining the coherence scale of the interstellar magnetic field using TeV gamma-ray observations of supernova remnants

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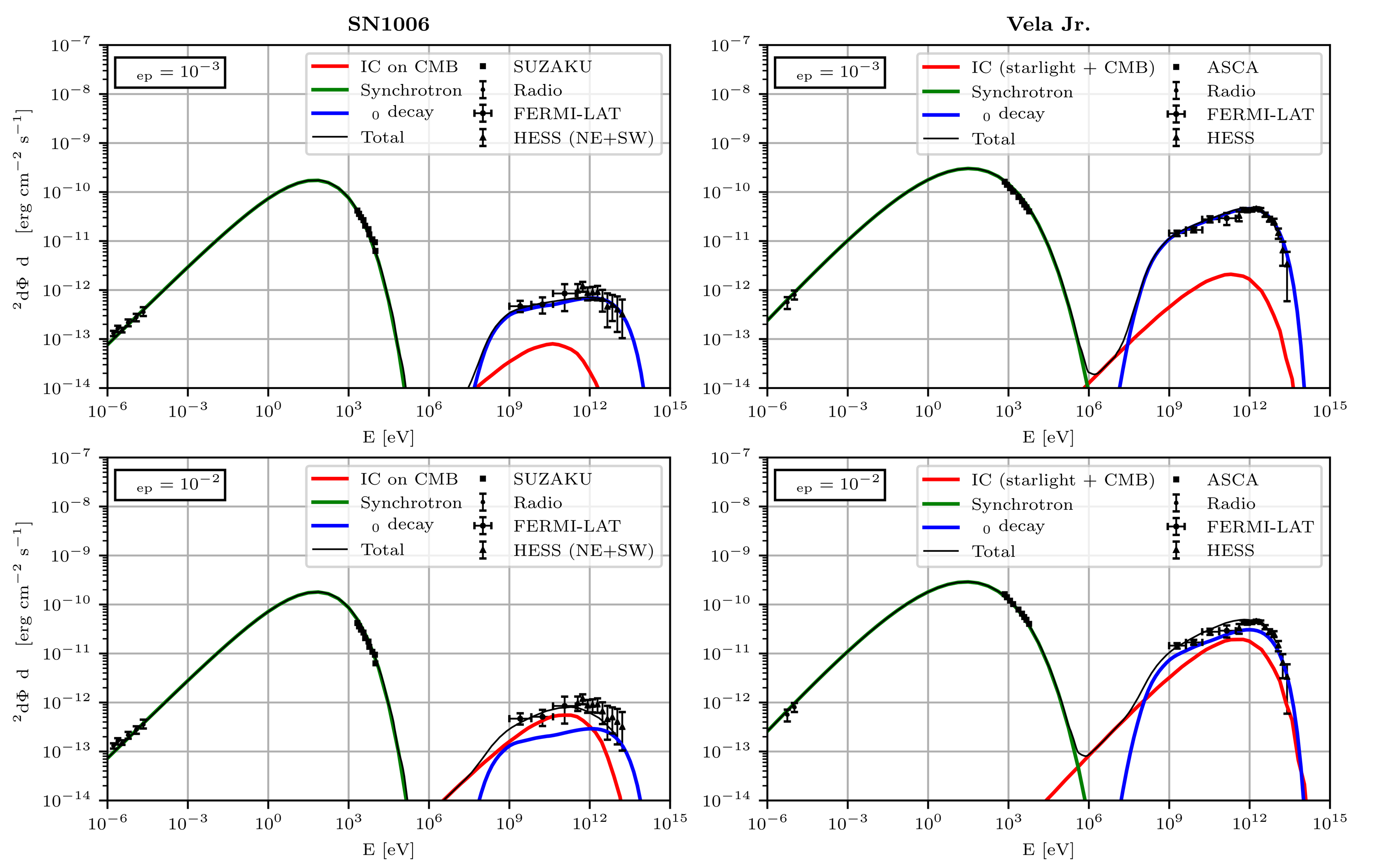
Motivation

Galactic cosmic rays are believed to be accelerated via first-order Fermi acceleration at expanding shocks of supernova remnants (SNRs). These explosions convert roughly 10% of their energy into cosmic rays (CR). In the years hadronic vs. leptonic models have been proposed, in particular neutral pion decay appears promising for explaining the TeV gamma-ray emission. Here, we show that the morphology of this emission derives from a combination of obliquity-dependent shock acceleration and turbulent magnetic fields in a cold interstellar medium. Diffusive shock acceleration is a universal process that energizes particles at collisionless shocks. The process enables a small fraction of particles that impinges on the shock to gain more energy than the average through multiple shock crossings. Particle-in-cell simulations showed that the efficiency of this process depends on the angle between the magnetic field and the shock normal. In particular, quasi-parallel shocks are most efficient while quasi-perpendicular shocks are inefficient in accelerating CRs.

Data on SNR

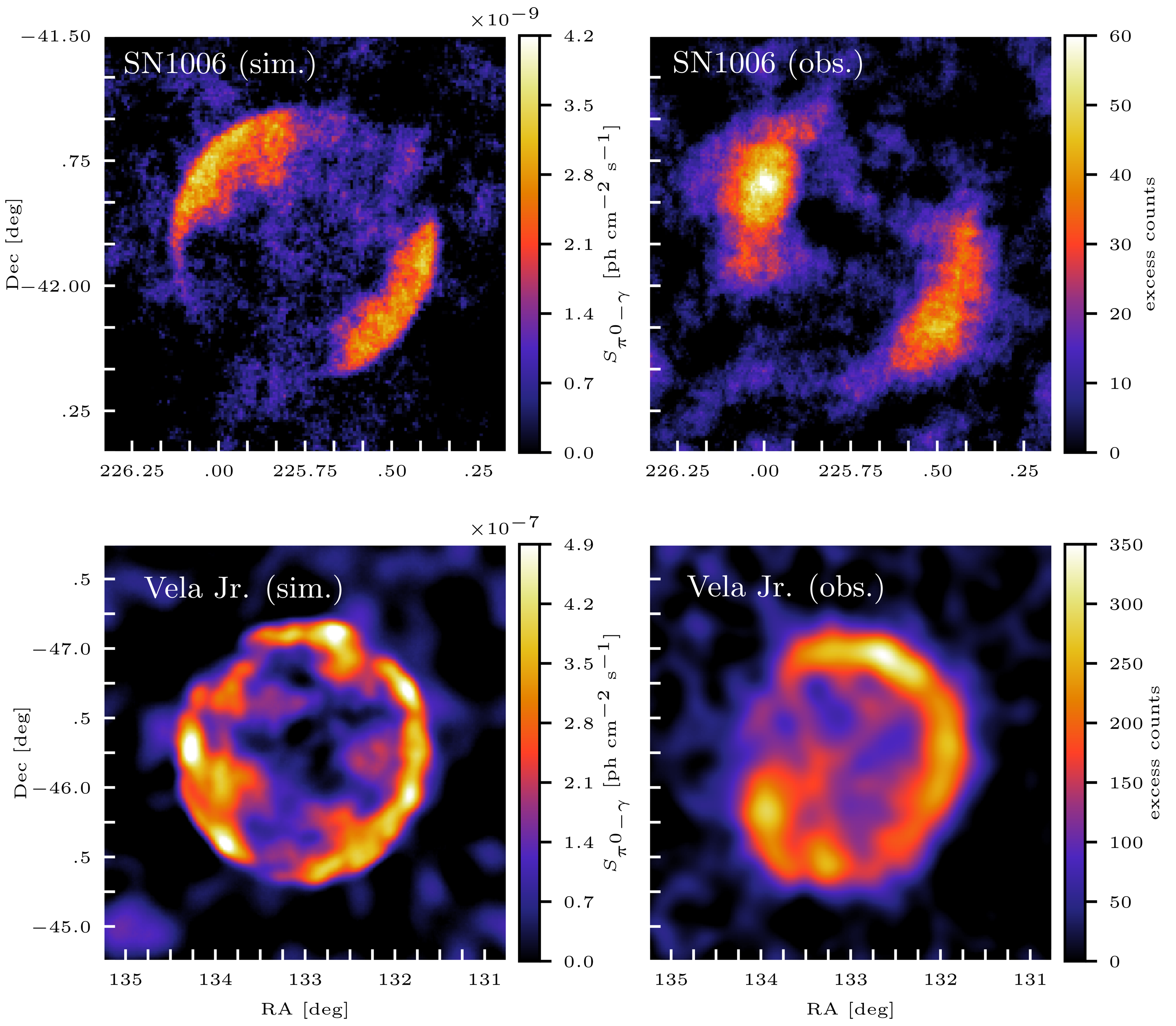


Multi-frequency spectra of SN1006 (left-hand panels) and Vela Jr. (right-hand panels). The top panels show a hadronic scenario for both remnants assuming an electron-to-proton ratio of $K_{ep} = 10^{-3}$. The bottom panels show a mixed hadronic-leptonic scenario with $K_{ep} = 10^{-2}$. We account for the following processes: synchrotron radiation from primary electrons (green lines), IC scattering on the CMB for SN1006 and additionally on starlight for Vela Jr. (red lines) and hadronic interactions (blue lines).

Table: Comparison of simulation and observational parameters. The flux is expressed in units of $[10^{-12}\text{ph cm}^{-2}\text{ s}^{-1}]$. The superscripts **H** and **M** denote the parameters of the pure hadronic and mixed hadronic/leptonic models, respectively.

SNR	SN1006		Vela Jr.	
Parameter	**Simulation**	**Observation**	**Simulation**	**Observation**
diameter θ_s [deg]	0.5	0.5	2	2
Γ_{HE}	1.95	1.79 ± 0.44	1.81	1.85 ± 0.24
Γ_{TeV}	2.15	2.30 ± 0.15	2.11	2.24 ± 0.19
$\mathcal{F}_\gamma(> 1\text{TeV})$	0.39	0.39 ± 0.08	23.4	23.4 ± 5.6
n [cm^{-3}]	$0.128^{\mathbf{H}}$, $0.09^{\mathbf{M}}$	< 0.3	$0.323^{\mathbf{H}}$, $0.238^{\mathbf{M}}$	< 0.4
D [pc]	$1530^{\mathbf{H}}$, $1650^{\mathbf{M}}$	1450-2200	$350^{\mathbf{H}}$, $300^{\mathbf{M}}$	200-750
diameter d_s [pc]	$13.3^{\mathbf{H}}$, $14.3^{\mathbf{M}}$	12.6-19.2	$12.2^{\mathbf{H}}$, $10.5^{\mathbf{M}}$	$7 - 26$
t [yrs]	1012	1012	$1200^{\mathbf{H}}$, $690^{\mathbf{M}}$	680-4300
v [km s^{-1}]	2800	2790-4980	$1970^{\mathbf{H}}$, $2900^{\mathbf{M}}$	> 1000
B [μG]	$200^{\mathbf{H}}$, $80^{\mathbf{M}}$	—	$40^{\mathbf{H}}$, $10^{\mathbf{M}}$	—
$E_{\text{p,cut}}$[TeV]	200	—	100	—
$E_{\text{e,cut}}$[TeV]	$1.7^{\mathbf{H}}$, $3^{\mathbf{M}}$	—	$0.25^{\mathbf{H}}$, $0.4^{\mathbf{M}}$	—
β_{p}	2	—	2	—
β_{e}	0.7	—	0.4	—
λ_B [pc]	$> 200^{+80}_{-10}$	—	$10^{+10}_{-3.3}$	—

Observations and simulations



Comparison between simulated (left) and observed (right) gamma-ray emission. Top left: the model for SN1006 uses a superposition of a homogeneous magnetic field along the anti-diagonal and a mildly turbulent magnetic field with a coherence length equal to the box size, both with an obliquity-dependent shock acceleration efficiency. The result are two gamma-ray emission lobes located exactly in the same regions of the actual image reconstructed from the observed X-ray flux. Instead, the model of Vela Jr. at bottom left uses a mildly turbulent magnetic field with a correlation scale equal to a third the box size. Coupled with an obliquity-dependent efficiency, this allows to create a filamentous and corrugated structure in the gamma-ray emission without varying the ambient density. The scale of the CR-rich patches enable to give a rough estimate of the coherence length of the magnetic field in the galactic region where the SNR is located. Right: acceptance-corrected smoother excess map for SN1006 [1] (top) and Vela Jr. [2] (bottom).

Summary

We can predict with geometrical arguments that the averaged efficiency in converting dissipated energy into CRs is about 1/3 of the maximum acceleration efficiency at quasi-parallel shocks and the coherence length of the magnetic field. The simulated models show good agreement with TeV observations of shell-type SNRs. Comparing our simulations to observed TeV maps of shell-type SNRs enables us to estimate λ_B of the unperturbed ISM before it encountered the SNR blast wave. Assuming statistical homogeneity, we constrain λ_B in the vicinity of SN1006 and Vela Jr. to $> 200^{+80}_{-10}$ pc and $10^{+10}_{-3.3}$ pc, respectively [4]. If obliquity-dependent diffusive shock acceleration also applies to electrons, we could produce similar synthetic TeV maps in the leptonic model to constrain the magnetic coherence length. If electron acceleration were independent of magnetic obliquity then this work would provide strong evidence for the hadronic scenario in shell-type SNRs as the necessary element to explain the patchy TeV emission. Moreover, here we show that the hadronic model is able to explain shell-type SNR morphologies, which naturally emerge in our simulations due to the peaked density at the shock in combination with the slowly decreasing CR pressure profile [3].

References

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[4] Pais et. al (2019), preprint, arXiv:1805.03216 [astro-ph.HE].