Ultra-High-Energy γ-ray Halos around Short-Lived Galactic PeVatrons

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Are SNRs the Galactic PeVatrons?

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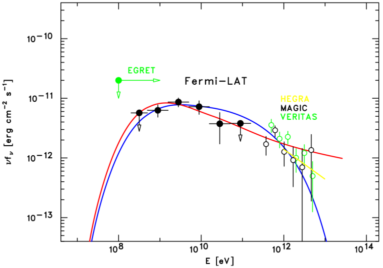
- many SNRs now detected in GeV (HE) and TeV (VHE) γ-rays
- in at least some cases, γ-ray emission likely of hadronic origin
- *(non-linear diffusive shock acceleration)* (NLDSA) theory predicts $\Gamma \approx 2.0 - 2.1$; then observe cutoffs $E_{\gamma,\mathrm{cut}} \sim 10\,\mathrm{TeV}$



e.g. **Cas A** (Abdo et al. 2010)

GeV / TeV hadronic spectral fits imply either :

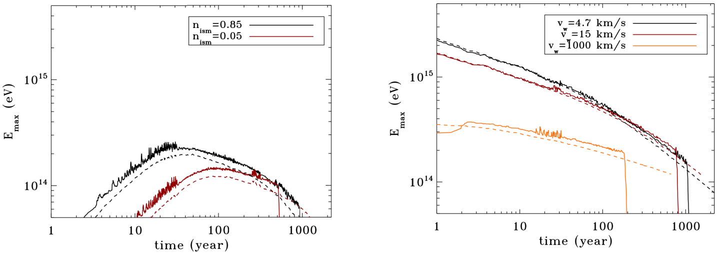
- energy cutoff at 10 TeV (and $\Gamma = 2.1$)
- steeper spectral index $\Gamma = 2.3$ (no cutoff)

$\Rightarrow$ no evidence that **any** known SNR is currently accelerating cosmic rays to PeV energies (with theoretically expected spectrum)

Where are the PeVatrons ? (Lemoine-Goumard 2012)

Theoretical solution: short-lived PeVatrons?

- if SNRs are the main sources of Galactic cosmic rays, they must at some stage of their evolution be “PeVatrons”
- challenging theoretically to reach $E_{\max} \sim 3$ PeV for protons (need high enough δB to confine them near the shock)
- **Schure & Bell (2013a)** consider Bell’s non-resonant hybrid instability for SNRs evolving in pre-supernova stellar winds



- “[...] we get to about a PeV but not too much beyond, and only for SNRs younger than a few decades.”
- related suggestions (some on shorter time scales) by Völk & Biermann (1988), Tatischeff (2009), Renaud et al. *(in prep.)*

Implications of short-lived PeVatron scenarios

Hypothesis

- the sources of GCRs ("PeVatrons") reach $E_{p,\max} \sim$ few PeV for only a brief ($\Delta t \leq 10$ yr) period (e.g. the early SNR phase)

Consequences

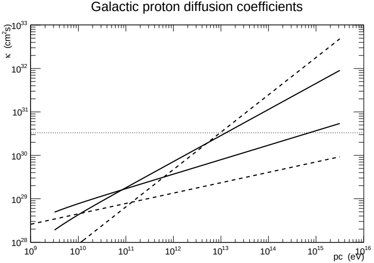
- the current *confined* accelerated particle spectrum deduced from γ-ray observations of SNRs will cut off at $E_{\rm esc}(t) \ll 3$ PeV
  (would need to be very lucky to catch one "in the act")
- recent PeVatrons injected the *escaped* PeV cosmic rays with $E > E_{\rm esc}(t)$ into the surrounding medium, during a short time
  $\rightarrow$ could such PeV CRs be detectable through their interaction with the ISM, yielding **PeVatron halos** in γ-rays?

Required cosmic-ray yield per PeVatron

- must replenish Galactic CR density against (diffusive) escape:

$$n(E) = n_0 E^{-2.68}, \qquad t_{\rm res}(E) \approx H^2/[2\kappa(E)]$$

- Galactic diffusion coefficient $\kappa(E)$ at PeV energies? Extrapolate from lower-energy constraints (main uncertainty is in δ):



$$\kappa(E) \approx \kappa_0 E^{\delta}$$

Trotta et al. 2011 *(solid)*:
$\delta = \frac{1}{3}$ and 0.6

Putze et al. 2010 *(dashed)*:
$\delta = 0.24$ and 0.86

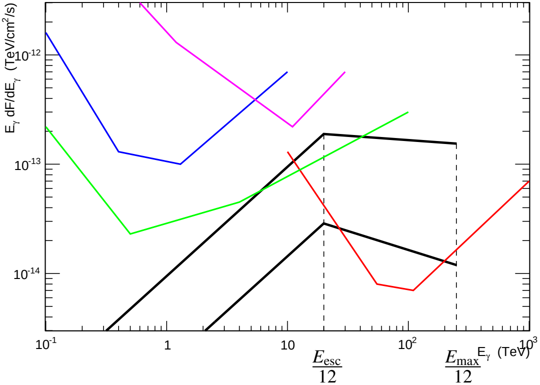
- assume PeVatrons at Galactic supernova rate: $1/\tau \approx 3/(100\,\mathrm{yr})$
- (time-integrated) PeVatron *escaping* particle spectrum:

$$Q(E) = \frac{V_{\rm Gal}\, n(E)\, \tau}{t_{\rm res}} = \frac{4\pi R_{\rm Gal}^2\, n_0\, \tau\, \kappa_0}{H} \times E^{-2.68+\delta}$$

PeVatron halo γ-ray luminosity

- for $E > E_{\rm esc}(t)$, CRs already propagating in interstellar medium
- CR p + ISM $p \rightarrow p + p + \pi$'s, and $\pi^0 \rightarrow 2\gamma$:

  total $L(E_\gamma) \propto n_{\rm ISM}\, Q(12\, E_\gamma)$, $\quad$ for $E_\gamma \geq E_{\rm esc}(t)/12$



(point-source) sensitivities:

HESS/VERITAS

HAWC

CTA

LHAASO-KM2A

- predicted fluxes for the halo of e.g. **Cas A** (and $n_{\rm ISM}$=1 cm^{-3}) could be **detectable** by LHAASO-KM2A, if less extended than a few square degrees

Halo extent: diffusive regime

- at sufficiently large times, propagation will be diffusive:

$$R_h(E,t) \approx \sqrt{2\kappa(E)t}$$

- but this requires isotropisation of initial direction angle α:

$$\langle \Delta\alpha^2 \rangle \equiv \nu_\alpha t \approx \frac{c^2 t}{3\kappa(E)} \geq 1 \quad \Leftrightarrow \quad t \geq t_{\rm iso}(E) \equiv \frac{3\kappa(E)}{c^2}$$

$$t_{\rm iso}(E) = 4.2 \left(\frac{E_{\rm GeV}}{3}\right)^{1/3} \,{\rm yr} \approx 300\,{\rm yr} \quad {\rm for}\ E = 1\,{\rm PeV},\ \delta = 1/3$$

- for cases of interest, isotropisation borderline for $\delta = 1/3$, not yet effective for $\delta = 1/2$ or larger: free streaming at (a fraction of) the speed of light

- *Caveat:* generation of self-excited waves by streaming CRs might make isotropisation faster, and diffusive regime start earlier (with smaller $\kappa(E)$ $\Rightarrow$ more effective confinement)

Halo extent: free-streaming regime

- with typical ISM scattering wave amplitudes, transition between free-streaming and diffusive regimes can be described as:

$$R_h(E,t) \leq \min\left\{ct, \sqrt{2\kappa(E)t}\right\}$$

- the free-streaming limit implies

$$R_h(t) \leq 30.7\,\mathrm{pc}\left(\frac{t}{100\,\mathrm{yr}}\right) \quad = \quad 107\,\mathrm{pc}\ \text{for}\ \textbf{Cas A}\ (t \approx 350\,\mathrm{yr})$$

- if this were the apparent size of the halo, at $D = 3.4\,\mathrm{kpc}$, would have angular size $\theta_h \leq 1.8°$
- **N.B.**: this extent is along the regular magnetic field direction; *perpendicular* extent due to field-line wandering, much smaller
- but (at least in free-streaming regime) PeVatron halo appearance affected by beaming and light-travel-time effects

PeVatron halo appearance

Beaming

- π's from $p - p$ collisions beamed (with typical angle $1/\gamma_p$) in direction of CR proton
- γ-rays from π^0 decay beamed with typical angle $1/\gamma_\pi$

$\Rightarrow$ γ-ray emission from CRs travelling nearly along line of sight

Light travel time

- consider ISM magnetic field making angle ϕ with line of sight
- $r_\mathrm{L} \sim 1$ pc at 1 PeV $\Rightarrow$ escaping CRs are "gyrotropised"
- see emission from CRs with pitch angle $\alpha \approx \phi$; $v_\| \approx c \cos\phi$
- in free-streaming regime (neglecting pitch-angle scattering): (one-sided) distance in plane of sky $x_h(t) \approx ct \cos\phi \sin\phi$
- light travel time: $t_\mathrm{obs} \approx t\left(1 - \cos^2\phi\right) = t \sin^2\phi$

$\Rightarrow$ apparent sky velocity $v_\mathrm{app} \approx c/\tan\phi$ (can be superluminal!)

Summary and prospects

- if Galactic PeVatrons are short-lived, they are still surrounded by an over-density of *escaped* PeV cosmic rays, with radius

$$R_h(E,t) \le \min\left\{ct, \sqrt{2\kappa(E)t}\right\}$$

- the *ultra-high-energy* ($E_\gamma > 30\,\mathrm{TeV}$) γ-ray flux of such PeVatron halos may be detectable with planned experiments such as LHAASO-KM2
- such "halos" would extend along the local ISM magnetic field direction, with centroid displaced from the source
- the detection of such halos would provide **direct observational proof** of the acceleration of cosmic-rays up to the "knee" energy
- if detected, the energy-dependent size and shape of such halos could provide unique observational constraints on the transport properties of very-high-energy cosmic rays in the Galaxy

Supplementary slides

LHAASO project and km^2 array

- a next-generation high-altitude (4300 m) direct detector array
- prototype operating in Tibet; planned site in Yunnan, China

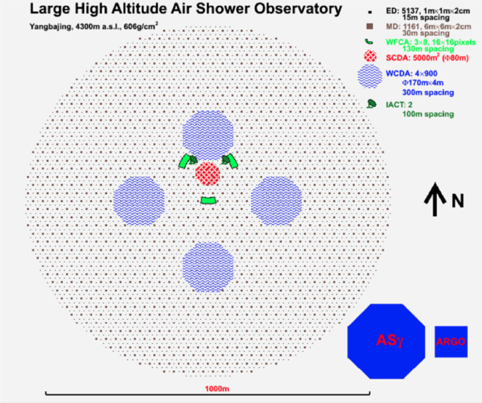
"Electron" Detectors

Muon Detectors

Wide FOV Cherenkov Array

Core Detector Array

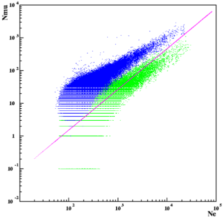
Water Cherenkov Detector Array



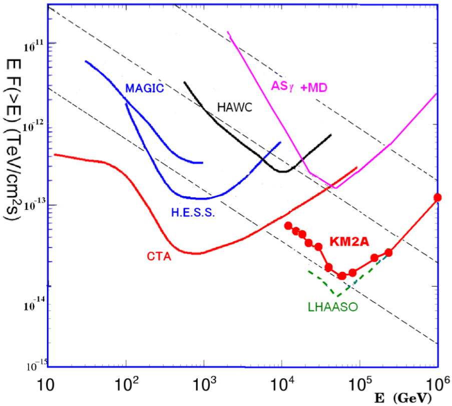
- KM2A for ultra-high-energy ($E > 30$ TeV) γ-ray astronomy:
  - surface scintillation detectors: large $A_{\rm eff} \sim 1\,{\rm km}^2$
  - muon detectors: very good hadron rejection ($>99.9\%$ of p)

LHAASO-KM2A Sensitivity

γ / p separation



(1 year of operation)



(Cui & Ma for LHAASO, 2009 ICRC)