SNRs as PeVatron candidates for CTA

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2018|10|08
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• Supernova Remnants as PeVatron candidates
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Cherenkov Telescope Array (CTA)

Small-sized telescopes (SST): 1 TeV - 300 TeV
Medium-sized telescopes (MST): 100 GeV - 10 TeV
Large-sized telescopes (LST): 20 GeV - 200 GeV

North site: La Palma (Spain)  South site: Paranal (Chile)
CTA detect the Cherenkov light induced by gamma-ray
LST, 2017-11, La Palma, Spain
CTA: Cosmic-rays PeVatron as a Key Science Project (KSP)

from Rene Ong (2015)
Cosmic-Rays accelerated up to 1 PeV

- PeVatrons: astrophysical object accelerated particles above 1 PeV (10^15eV).

- The energy of spectrum of Cosmic-Rays (CRs) extends until few PeV where it steepens originating the ‘knee’.

- Theoretical prediction and measurements of CR indicate that the CR should be accelerated up to 1 PeV in our Galaxy.
Supernova Remnants (SNRs) as promising Galactic PeVatron candidates

- The detection of SNRs with spectrum up to 100 TeV imply that they are one kinds of PeVatron candidates, because ~100 TeV photons are produced by ~ PeV protons. (observation)

- SNRs are able to satisfy the cosmic-ray energy requirement by converting the kinetic energy into accelerated particle. (theory)

- SNRs (and Pulsar Wind Nebulae) are the majority of Galactic poululation.
Proton-proton collision induces pion decay

For accelerated protons, hadronic interactions with ambient matter produce neutral pion, decaying into two γ-ray photons

\[
\pi^0 \rightarrow \gamma_1 + \gamma_2,
\]

\[
\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu,
\]

\[
\pi^- \rightarrow \mu^- + \bar{\nu}_\mu \rightarrow e^- + \bar{\nu}_e + \nu_\mu + \bar{\nu}_\mu.
\]
DC-1 data, Prod3b IRF and ctools

- Data Challenge one (DC-1): *simulated* data enable the CTA Consortium Science Working Group to derive science benchmarks for the CTA KSP.

- DC-1 includes Galactic Plane Scan (GPS) as one of the key science projects. We use GPS data to analyse SNRs.

- Prod3b Instrumental Response Functions (IRFs): the performance values are derived from Monte Carlo simulation of CTA instrument based on the CORSIKA air shower code.

- Ctools: a soft package developed for scientific analysis of CTA data. We run ctools pipeline to judge whether SNRs from TeVCat are considered in DC-1 GPS, and to draw the spectrums.
Low Galactic latitude from TeVCat

<table>
<thead>
<tr>
<th>SNR name</th>
<th>Galactic Longitude</th>
<th>Galactic Latitude</th>
<th>Type</th>
</tr>
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<td>HESS J1534—571</td>
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<td>HESS J1800—240C</td>
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<tr>
<td>HESS J1800—240A</td>
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<tr>
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<tr>
<td>SNR G015.4+00.1</td>
<td>15.41</td>
<td>0.16</td>
<td>Composite SNR</td>
</tr>
</tbody>
</table>
SNR interacting with Molecular Cloud Spectrum and Sensitivity

 Flux [erg cm$^{-2}$ s$^{-1}$] vs. Energy [TeV]

- SNR G318.2+00.1
- CTB 37A
- HESS J1745-303
- W28
- HESS J1800-240A
- W49B
- W51
- CTA north
- CTA south

logarithmic scale

- Energy range: $10^{-2}$ to $10^{2}$ TeV
- Flux range: $10^{-16}$ to $10^{-10}$ erg cm$^{-2}$ s$^{-1}$
Given that the MCMC procedure will sample the areas of the distribution with maximum value of the objective function, it is useful to define the objective function as the log-likelihood disregarding constant factors:

$$\ln \mathcal{L} \propto \sum_{i=1}^{N} \frac{(S(p_i^r E_i) - F_i)^2}{\sigma_i^2}.$$ 

The $\ln \mathcal{L}$ function in this assumption can be related to the $\chi^2$ parameter as $\chi^2 = -2 \ln \mathcal{L}$, so that maximization of the log-likelihood is equivalent to a minimization of $\chi^2$.

class naima.models.Synchrotron(particle_distribution, B=<Quantity 3.24e-06 G>, **kwargs)

Synchrotron emission from an electron population.

This class uses the approximation of the synchrotron emissivity in a random magnetic field of Aharonian, Kelner, and Prosekin 2010, PhysRev D 82, 3002 (arXiv:1006.1045).

Parameters: particle_distribution : function

Particle distribution function, taking electron energies as a Quantity array or float, and returning the particle energy density in units of number of electrons per unit energy as a Quantity array or float.

B : Quantity float instance, optional

Isotropic magnetic field strength. Default: equipartition with CMB (3.24e-6 G)

class naima.models.PionDecay(particle_distribution, nh=<Quantity 1.1 / cm3>, nuclear Enhancement=True, **kwargs)

Pion decay gamma-ray emission from a proton population.

Compute gamma-ray spectrum arising from the interaction of a relativistic proton distribution with stationary target protons using the parametrization of Kafexhiu et al. (2014).

If you use this class in your research, please consult and cite Kafexhiu, E., Aharonian, F., Taylor, A.M., & Vila, G.S. 2014, Physical Review D, 90, 123014.

Parameters: particle_distribution : function

Particle distribution function, taking proton energies as a Quantity array or float, and returning the particle energy density in units of number of protons per unit energy as a Quantity array or float.

nh : Quantity

Number density of the target protons. Default is 1 cm$^{-3}$. 


Radiation mechanism for SNRs
Four main non-thermal radiative mechanisms for producing $\gamma$-ray
Electron and proton follow exponential cutoff power-law

\[ f(E) = A \left( \frac{E}{E_0} \right)^{-\alpha} \exp\left( -\left( \frac{E}{E_{\text{cutoff}}} \right)^{\beta} \right) \]
HESS J1731-347 Photon spectrum of DC1

Energy [eV]

$E^2 dN/dE$ [ergs$^{-1}$ cm$^{-2}$]

$\Delta \sigma$

$10^{10}$  $10^{11}$  $10^{12}$  $10^{13}$  $10^{14}$  $10^{15}$
HESS J1731-347 Spectral Energy Distribution

![Graph of spectral energy distribution](image)

- **Energy**: $E^2 dN/dE$ [ergs$^{-1}$ cm$^{-2}$]
- **Energy Range**: $10^{-7}$ to $10^{14}$ eV
- **Energy Units**: ergs$^{-1}$ cm$^{-2}$

Legend:
- **PI**
- **IC**
- **Sync**
- **Sum**
Summary

- Proton cut-off energy values as PeVatron indicators.
- Distinguish pion-decay or inverse Compton process dominate SNRs radiation.
- I do not consider the energy dispersion.
- Reset the XML model definition file to smooth residuals maps.