Constraining the production of cosmic rays by pulsars

Mikhail Ivanov
EPFL & MSU & INR

w/ M. Pshirkov and G. Rubtsov
PRD, arXiv:1606.01480
TeVPA, CERN 12th September 2016
Hadronic Cosmic Rays

Required luminosity of CR sources: \( L \simeq 10^{41} \text{ erg/s} \)

Proven to be produced in supernova remnants (SNR W44, IC 433)

Some issues remain unsolved: not clear if enough, observed spectra are softer than theoretical etc.

Other sources also possible (superbubbles, pulsars)

\[
L \simeq 10^{41} \frac{\text{erg}}{\text{s}} \left[ \frac{E_{CR}^{tot}}{2 \times 10^{50} \text{ erg}} \right] \left[ \frac{R_{SN}}{1/50 \text{ yr}^{-1}} \right]
\]

\[
E_{rot} = \frac{I_{NS}\Omega^2}{2} \simeq 2 \times 10^{50} \text{ erg} \left[ \frac{I_{NS}}{10^{45} \text{ g cm}^2} \right] \left[ \frac{10 \text{ ms}}{P_{ini}} \right]^2
\]

Ackermann et al’11

Neronov, Semikoz (1201.1660)
Pulsars

May have enough initial rotation energy

Are well-established sources of $e^+e^-$ CRs; theory predicts that ions have even bigger energy

Hoshino, Gallant, Arons et al’92-94

Hard to extract the hadronic flux

There should be large ($\sim 100$ pc) diffusive gamma-ray halos around young pulsars

Neronov and Semikoz (1201.1660): blind search for gamma-ray halos $\Rightarrow$ pulsars $+$, SNR $-$
**Size:**

\[ r_{CR} \simeq 2 \sqrt{DT_{SD}} \]

\[ D = D_{28} \times 10^{28} \left( \frac{E_{CR}}{3 \text{ GeV}} \right)^{\delta} \text{ cm}^2/\text{s}, \]

\[ \delta = 0.4 \pm 0.1, \]

\[ r_{CR} \simeq 120 \times D_{28}^{1/2} \left( \frac{T_{SD}}{10 \text{ kyr}} \right)^{1/2} \left( \frac{E_{CR}}{1 \text{ TeV}} \right)^{0.2} \text{ pc} \]

\[ R_{halo} = \frac{r_{CR}}{r_s} \]

\[ \simeq 1.4^\circ D_{28}^{1/2} \left[ \frac{5 \text{ kpc}}{r_s} \right] \left( \frac{T_{SD}}{10 \text{ kyr}} \right)^{1/2} \left[ \frac{E_\gamma}{200 \text{ GeV}} \right]^{0.2} \]

\[ \sim 1 \text{ TeV in CRs} \]

**Luminosity:**

\[ L_{\gamma} \gtrsim 1 \text{ GeV} \sim \kappa \frac{E_{\text{halo}}}{t_{int}} \]

\[ \simeq 4 \times 10^{34} \left[ \frac{\kappa}{0.2} \right] \left[ \frac{E_{\text{halo}}}{2 \times 10^{50} \text{ erg}} \right] \left[ \frac{n_{\text{ISM}}}{1 \text{ cm}^{-3}} \right] \text{ erg/s} \]
Pulsar sample

- Young and close: \( T_{SD} < 30 \) kyr, \( r_s < 5 \) kpc

- Away from the Galactic plane and center:
  \[ 15^\circ < l < 345^\circ, \quad |b| > 1^\circ \]
### Pulsar sample

<table>
<thead>
<tr>
<th>PSRJ</th>
<th>l</th>
<th>b</th>
<th>$r_s$, kpc</th>
<th>$T_{SD}$, kyr</th>
<th>$\dot{E}$, erg/s</th>
<th>$P$, s</th>
</tr>
</thead>
<tbody>
<tr>
<td>J0007+7303</td>
<td>119.66</td>
<td>10.46</td>
<td>1.40</td>
<td>13.9</td>
<td>$4.5 \times 10^{35}$</td>
<td>0.32</td>
</tr>
<tr>
<td>J0501+4516</td>
<td>161.55</td>
<td>1.95</td>
<td>2.20</td>
<td>15.7</td>
<td>$1.2 \times 10^{33}$</td>
<td>5.8</td>
</tr>
<tr>
<td>J1709-4429</td>
<td>343.10</td>
<td>-2.69</td>
<td>2.60</td>
<td>17.5</td>
<td>$3.4 \times 10^{36}$</td>
<td>0.10</td>
</tr>
<tr>
<td>J2229+6114</td>
<td>106.65</td>
<td>2.95</td>
<td>3.00</td>
<td>10.5</td>
<td>$2.2 \times 10^{36}$</td>
<td>0.052</td>
</tr>
<tr>
<td>J0205+6449</td>
<td>130.72</td>
<td>3.08</td>
<td>3.20</td>
<td>5.37</td>
<td>$2.7 \times 10^{37}$</td>
<td>0.065</td>
</tr>
<tr>
<td>J1357-6429</td>
<td>309.92</td>
<td>-2.51</td>
<td>4.09</td>
<td>7.31</td>
<td>$3.1 \times 10^{36}$</td>
<td>0.17</td>
</tr>
<tr>
<td>J0534+2200</td>
<td>184.56</td>
<td>-5.78</td>
<td>2.00</td>
<td>1.26</td>
<td>$4.5 \times 10^{38}$</td>
<td>0.033</td>
</tr>
<tr>
<td>J1513-5908</td>
<td>320.32</td>
<td>-1.16</td>
<td>4.40</td>
<td>1.56</td>
<td>$1.7 \times 10^{37}$</td>
<td>0.15</td>
</tr>
</tbody>
</table>

Credits: ATNF
Method

- 7 year Fermi-LAT data and Fermi-LAT software

  For each pulsar:

  - Take all known 3FGL sources within 10° but allow their parameters to vary during *gtlike* (likelihood optimization routine)

  - Add to the source model uniformly bright round halo with a desired radius 0.1° – 5° with a power-law spectrum

  - Split the data into 3 energy bins (the size is different!)
    - 1 - 10 GeV, 10 - 100 GeV, and 100 - 500 GeV

  - *gtlike* it and check out the fit

  - Study the distribution of Test Statistics

    \[ TS = -2 \ln \left( \frac{L_{\text{max,0}}}{L_{\text{max,1}}} \right) \]

    \[ \# \text{ of } \sigma \approx \sqrt{TS} \]

  n.b. Rule of thumb:
FIG. 7. TS (R_halo) curves for the simulated bright gamma-ray halo around the pulsar PSR J0007+7303 for the spectral indices \( \Gamma = 2.4 \) (upper panel) and \( \Gamma = 2 \) (lower panel). The results of the analysis in different energy bands are shown as a black solid line for 100-500 GeV, a blue dashed line for 10-100 GeV, and a red dotted line for 1-10 GeV. Vertical arrows show the sizes of the halos that were input into the simulations.

Apart from the pulsar itself, there are 51 other LAT sources in the corresponding 10\(^2\) RoI. The pulsar of interest is very young (\( T_{SD} \ll 1 \text{ kyr} \)) and has a significant energy loss rate (\( \dot{E} \ll 10^{37} \text{ erg/s} \)). The halo around this pulsar should be quite small; see Table II.

To generate the Fermi-LAT events we made use of the gtobssim utility. For either pulsar we simulated events in the energy range 1-500 GeV for the relevant time interval (361 weeks) in the 10\(^2\) RoI around the pulsar. The input model included all the LAT point and extended sources located within the RoI, the galactic and isotropic background, and the gamma-ray halo around the chosen pulsar. Spectral parameters and photon fluxes for the 3FGL sources were taken directly from the 3FGL catalogue, and the recommended values were chosen for the analysis.

As discussed in Sec. V, for either pulsar we simulated two types of halos: the bright one and the faint one. For the bright halos [case (a) in what follows] we assumed the fluxes of order (11) in the energy bin 100-500 GeV. Having fixed the flux in the range 100-500 GeV [Eq. (11)] and assuming a simple power-law spectrum of a halo, \( \frac{dN}{dE} = A_0 \times E^{\Gamma} \), we computed the normalization factor \( A_0 \) for two particular choices of the spectral index: \( \Gamma = 2.4 \) and \( \Gamma = 2 \). This yielded the halo fluxes in the energy bands 1-10 GeV and 10-100 GeV.

In the case of a bright halo around the pulsar PSR J1513-5908 we fixed the flux (11) at \( r_s = 4.4 \text{ kpc} \).
depends drastically upon the spectral index. If the halo we fixed the flux in the energy bin 10-100 GeV, the signal spectrum with depending on the spectral index. A soft spectrum with the spectrum. The excess in the energy bin 10-100 GeV PSR J0007+7303 case. Given that for either spectral in-bias is, however, not as strong as the one we saw in the detected sizes of the halo at energies above 10 GeV. This of a faint halo, the detection with significance one can still see a small o and after that have very moderate dependence on 10-100 GeV) the more statistics. In the bin 100-500 GeV the are present) and weakens at lower energies which contain bias is quite strong above 100-500 GeV (where less events which indicates that the likelihood optimization proce-

Simulations: TS (flux) scaling

![Graph showing TS scaling]

**best fits:**

\[
TS_{1-10} \approx 100 \left[ \frac{F_{1-10 \text{ GeV}}}{4.6 \times 10^{-9} \text{ ph/cm}^2 \text{s}} \right]^{b_1},
\]

\[
b_1 = 1.54 \pm 0.06,
\]

\[
TS_{10-100} \approx 100 \left[ \frac{F_{10-100 \text{ GeV}}}{5.7 \times 10^{-10} \text{ ph/cm}^2 \text{s}} \right]^{b_2},
\]

\[
b_2 = 1.42 \pm 0.14,
\]

\[
TS_{100-500} \approx 100 \left[ \frac{F_{100-500 \text{ GeV}}}{2.4 \times 10^{-10} \text{ ph/cm}^2 \text{s}} \right]^{b_3},
\]

\[
b_3 = 1.33 \pm 0.10.
\]

**a halo with a given flux yields detection @ which TS ?**
FIG. 3. TS ($R_{\text{halo}}$) curves for PSR J0007+7303 (upper panel) and PSR J0501+4516 (lower panel). The results of the analysis in different energy bands are shown as a black solid line for 100-500 GeV, a blue dashed line for 10-100 GeV, and a red dotted line for 1-10 GeV. Vertical arrows show the sizes of the halos that are expected from the estimate ($8\pm2$).

When analyzing the region near the pulsar PSR J0501+4516 we find an excess in the energy bands 10-100 GeV and 1-10 GeV at statistical significance TS' = 45 and TS' = 55, respectively, and the corresponding halo size is roughly $1.5\pm0.3$ (see the lower panel of Fig. 3).

In fact, the region of interest has been studied in detail in Ref. [59]. This study has revealed the presence of a significantly extended ($R_{\text{halo}}=1.2\pm0.3$) gamma-ray source at the position of SNR HB9 [SNR G160.4+02.8, ($l, b$) = (160.4, 2.75)]. With the new Fermi-LAT data we rediscovered this source, but its interpretation as a CR halo does not seem to be plausible. The angular size of a CR halo is expected to increase with energy, while the size of the observed emission stays nearly similar in both energy bins, which suggests that this emission may be attributable to a SNR. Because of this source, it is practically impossible to extract the signal from a hypothetical gamma-ray halo. One can, however, place a trivial bound from the fact that the halo flux in the energy bin 1-10 GeV is smaller than the total observed flux. Using the best fit for the extended emission at $R_{\text{halo}}=1.9$, we get

$$F_{10 \text{ GeV}} < F_{10 \text{ GeV}} \text{tot} = \left(2.82 \pm 0.42\right) \times 10^{-9} \text{ ph/cm}^2\text{s}.$$  

Assuming the spectral index of a halo above 10 GeV = 2.4, this yields the following bounds on the overall flux and luminosity of the halo above 1 GeV:

$$F_{E_{\text{1 GeV}}} < 1.7 \times 10^{11} \text{ erg/cm}^2\text{s}$$

and

$$L_{E_{\text{1 GeV}}} < 9.3 \times 10^{33} \text{ erg/s}.$$  

The case of $E=2\pi$ will be discussed below.

FIG. 4. TS ($R_{\text{halo}}$) curves for PSR J1709-4429 (upper panel) and PSR J2229+6114 (lower panel). Vertical arrows show the sizes of the halos that are expected from the estimate ($8\pm2$).
There are already PWN and SNR around this pulsar but might also be a halo! one has to disentangle between other sources there

\[ L_{E_{\gamma} \geq 1 \text{ GeV}} \sim 3.0 \times 10^{33} \text{ erg/s}. \]

\[ E^{\text{halo}}_{CR} \sim (2 - 4) \times 10^{50} \text{ erg}. \]

\[ F^{1-10 \text{ GeV}} = (3.53 \pm 0.23) \times 10^{-9} \text{ photons/cm}^2\text{s}, \]
\[ \Gamma = 2.798 \pm 0.081. \]
Preliminary update in progress...
Constraints

No halo seen for other pulsars

Nonobservation of halos:

\[ TS_{1-10} < 50 \]

\[ F^{1-10 \text{ GeV}} < 3.0 \times 10^{-9} \text{ ph/cm}^2\text{s} \]

\[ L_{\gamma}^{\text{halo}} \lesssim (1 - 2) \times 10^{34} \text{ erg/s} \]
Discussion

\[
\frac{\mathcal{E}^{\text{halo}}_{\text{CR}}}{2 \times 10^{50} \text{ erg}} \sim \left[ \frac{L^{\text{halo}}_\gamma}{2 \times 10^{34} \text{ erg/s}} \right] \left[ \frac{1 \text{ cm}^{-3}}{n_{\text{ISM}}} \right]
\]

Nonobservation of halos (fixed ISM density):

\[
L^{\text{halo}}_\gamma \lesssim (1 - 2) \times 10^{34} \text{ erg/s}
\]

\[
\mathcal{E}^{\text{halo}}_{\text{CR}} \lesssim (0.5 - 1) \times 10^{50} \text{ erg}
\]

Degeneracy with ISM density:

\[
n_{\text{ISM}} \simeq 0.3 \div 1 \text{ cm}^{-3}
\]

\[
\mathcal{E}^{\text{halo}}_{\text{CR}} \lesssim (0.5 - 3) \times 10^{50} \text{ erg}
\]

we need to explain all CRs with pulsars
(scatter = uncertainty in birthrates: 1 per 30-120 yr)
Conclusions:

- Pulsars might be sources of hadronic CRs: diffusive gamma-ray halos to test this scenario

- One candidate is found, thorough study required

- Apart from that, no definitive diffusive gamma-ray halos were found

- Bounds on luminosity \text{\rightarrow} bounds on CR flux

- Pulsars are pinned down as main CR factories (not completely ruled out though! beware of degeneracies and uncertainties)
Thank you for your attention!
Backup slides
Why only above 1 GeV?

1) @ 1 GeV the two coincide

\[ R_{\text{SNR}} = \frac{r_{\text{SNR}}}{r_s} \simeq 0.1^\circ \left[ \frac{5 \text{kpc}}{r_s} \right] \left[ \frac{t}{10 \text{ kyr}} \right]^{0.4} \times \left[ \frac{\mathcal{E}_{\text{SN}}}{10^{51} \text{erg}} \right]^{0.2} \left[ \frac{1 \text{ cm}^{-3}}{n_{\text{ISM}}} \right]^{0.2} \]

\[ R_{\text{halo}} = \frac{r_{\text{CR}}}{r_s} \simeq 1.4^\circ D_{28}^{1/2} \left[ \frac{5 \text{kpc}}{r_s} \right] \left[ \frac{T_{\text{SD}}}{10 \text{ kyr}} \right]^{1/2} \left[ \frac{E_\gamma}{200 \text{ GeV}} \right]^{0.2} \]

2) LAT PSF is big: localization capability reduced

![Graph showing containment angle vs. energy (MeV)]
PSR J0007+7303

TS
R \text{halo, degrees}
100-500 GeV
10-100 GeV
1-10 GeV

PSR J0501+4516

TS
R \text{halo, degrees}
100-500 GeV
10-100 GeV
1-10 GeV

FIG. 3. TS(R \text{halo}) curves for PSR J0007+7303 (upper panel) and PSR J0501+4516 (lower panel). The results of the analysis in different energy bands are shown as a black solid line for 100-500 GeV, a blue dashed line for 10-100 GeV, and a red dotted line for 1-10 GeV. Vertical arrows show the sizes of the halos that are expected from the estimate. Spectral parameters free during our analysis. Their values for PSR J0007+7303 can be found in Appendix D.

2) When analyzing the region near the pulsar PSR J0501+4516 we find an excess in the energy bands 10-100 GeV and 1-10 GeV at statistical significance TS = 45 and TS = 55, respectively, and the corresponding halo size is roughly 1.5. (see the lower panel of Fig. 3).

In fact, the region of interest has been studied in detail in Ref. [59]. This study has revealed the presence of a significantly extended ($R = 1.2 \pm 0.3$) gamma-ray source at the position of SNR HB9 (SNR G160.4 + 02.8, $(l, b) = (160.4, 2.75)$). With the new Fermi-LAT data we rediscovered this source, but its interpretation as a CR halo does not seem to be plausible. The angular size of a CR halo is expected to increase with energy, while the size of the observed emission stays nearly similar in both energy bins, which suggests that this emission may be attributable to a SNR. Because of this source, it is...
## Pulsar sample

<table>
<thead>
<tr>
<th>PSRJ</th>
<th>l</th>
<th>b</th>
<th>$r_s$, kpc</th>
<th>$T_{SD}$, kyr</th>
<th>$\dot{E}$, erg/s</th>
<th>$P$, s</th>
</tr>
</thead>
<tbody>
<tr>
<td>J0007+7303</td>
<td>119.66</td>
<td>10.46</td>
<td>1.40</td>
<td>13.9</td>
<td>$4.5 \times 10^{35}$</td>
<td>0.32</td>
</tr>
<tr>
<td>J0501+4516</td>
<td>161.55</td>
<td>1.95</td>
<td>2.20</td>
<td>15.7</td>
<td>$1.2 \times 10^{33}$</td>
<td>5.8</td>
</tr>
<tr>
<td>J1709-4429</td>
<td>343.10</td>
<td>-2.69</td>
<td>2.60</td>
<td>17.5</td>
<td>$3.4 \times 10^{36}$</td>
<td>0.10</td>
</tr>
<tr>
<td>J2229+6114</td>
<td>106.65</td>
<td>2.95</td>
<td>3.00</td>
<td>10.5</td>
<td>$2.2 \times 10^{36}$</td>
<td>0.052</td>
</tr>
<tr>
<td>J0205+6449</td>
<td>130.72</td>
<td>3.08</td>
<td>3.20</td>
<td>5.37</td>
<td>$2.7 \times 10^{37}$</td>
<td>0.065</td>
</tr>
<tr>
<td>J1357-6429</td>
<td>309.92</td>
<td>-2.51</td>
<td>4.09</td>
<td>7.31</td>
<td>$3.1 \times 10^{36}$</td>
<td>0.17</td>
</tr>
<tr>
<td>J0534+2200</td>
<td>184.56</td>
<td>-5.78</td>
<td>2.00</td>
<td>1.26</td>
<td>$4.5 \times 10^{38}$</td>
<td>0.033</td>
</tr>
<tr>
<td>J1513-5908</td>
<td>320.32</td>
<td>-1.16</td>
<td>4.40</td>
<td>1.56</td>
<td>$1.7 \times 10^{37}$</td>
<td>0.15</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>PSRJ</th>
<th>$R_{halo}(1$ GeV)</th>
<th>$R_{halo}(10$ GeV)</th>
<th>$R_{halo}(100$ GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>J0007+7303</td>
<td>$2.0^\circ$</td>
<td>$3.2^\circ$</td>
<td>$5.0^\circ$</td>
</tr>
<tr>
<td>J0501+4516</td>
<td>$1.4^\circ$</td>
<td>$2.2^\circ$</td>
<td>$3.5^\circ$</td>
</tr>
<tr>
<td>J1709-4429</td>
<td>$1.2^\circ$</td>
<td>$2.0^\circ$</td>
<td>$3.1^\circ$</td>
</tr>
<tr>
<td>J2229+6114</td>
<td>$0.8^\circ$</td>
<td>$1.3^\circ$</td>
<td>$2.1^\circ$</td>
</tr>
<tr>
<td>J0205+6449</td>
<td>$0.6^\circ$</td>
<td>$0.9^\circ$</td>
<td>$1.4^\circ$</td>
</tr>
<tr>
<td>J1357-6429</td>
<td>$0.5^\circ$</td>
<td>$0.8^\circ$</td>
<td>$1.3^\circ$</td>
</tr>
<tr>
<td>J0534+2200</td>
<td>$0.4^\circ$</td>
<td>$0.7^\circ$</td>
<td>$1.1^\circ$</td>
</tr>
<tr>
<td>J1513-5908</td>
<td>$0.2^\circ$</td>
<td>$0.4^\circ$</td>
<td>$0.6^\circ$</td>
</tr>
</tbody>
</table>
Results

- **PSR J0205+6449**
  - 100-500 GeV
  - 10-100 GeV
  - 1-10 GeV

- **PSR J1357-6429**
  - 100-500 GeV
  - 10-100 GeV
  - 1-10 GeV

- **PSR J1513-5908**
  - 100-500 GeV
  - 10-100 GeV
  - 1-10 GeV

- **Crab, PSR J0534+2200**
  - 100-500 GeV
  - 10-100 GeV
  - 1-10 GeV
Results

PSR J2229+6114

100-500 GeV
10-100 GeV
1-10 GeV
The predicted flux from a molecular cloud illuminated (e.g., see Pedaletti et al. 2013) is expressed in TeV, the distance $D$ in kpc, the energy $E$ in $10^3$ GeV, and the mass $M$ in $10^5$ $M_\odot$. The distance is calculated above, one would have

$$D = \frac{E}{\kappa_s} = \frac{E}{\kappa_{s,\text{eff}}} = \frac{E}{\kappa_{s,\text{eff}} \times 10^3}$$

are n and $\kappa_{s,\text{eff}}$ is the enhancement factor of CRs, where $\kappa_{s,\text{eff}} = \kappa_s \times 10^3$. This is the enhancement factor of CRs, and the latter should be acting as a very powerful accelerator. Thus, for the TeV emission to originate in the velocity range of the HI shell found by Pineault et al. (1993). Radio contours are shown in green (Pineault et al. 1993). Radio contours are shown in green (Pineault et al. 1993). Radio contours are shown in green (Pineault et al. 1993). Radio contours are shown in green (Pineault et al. 1993). Radio contours are shown in green (Pineault et al. 1993). Radio contours are shown in green (Pineault et al. 1993). Radio contours are shown in green (Pineault et al. 1993). Radio contours are shown in green (Pineault et al. 1993).

The predicted flux from a molecular cloud embedded in a molecular cloud illumination (e.g., see Seward et al. 1995). Radio contours are shown in green (Pineault et al. 1995). Radio contours are shown in green (Pineault et al. 1995). Radio contours are shown in green (Pineault et al. 1995). Radio contours are shown in green (Pineault et al. 1995). Radio contours are shown in green (Pineault et al. 1995). Radio contours are shown in green (Pineault et al. 1995). Radio contours are shown in green (Pineault et al. 1995). Radio contours are shown in green (Pineault et al. 1995). Radio contours are shown in green (Pineault et al. 1995). Radio contours are shown in green (Pineault et al. 1995). Radio contours are shown in green (Pineault et al. 1995). Radio contours are shown in green (Pineault et al. 1995). Radio contours are shown in green (Pineault et al. 1995). Radio contours are shown in green (Pineault et al. 1995). Radio contours are shown in green (Pineault et al. 1995). Radio contours are shown in green (Pineault et al. 1995). Radio contours are shown in green (Pineault et al. 1995). Radio contours are shown in green (Pineault et al. 1995). Radio contours are shown in green (Pineault et al. 1995). Radio contours are shown in green (Pineault et al. 1995). Radio contours are shown in green (Pineault et al. 1995). Radio contours are shown in green (Pineault et al. 1995).