Middle-aged SNRs W44 & IC443 and Cosmic-Rays: most likely reacceleration

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ALL PARTICLE SPECTRUM

KNEE

SNR accelerate Galactic Cosmic-Rays

Need to distinguish hadronic and leptonic components

Gamma-ray emission below 200 MeV detected by AGILE from the SNR W44, then confirmed by Fermi-LAT, also in IC443

Cosmic-Rays in SNRs... but acceleration or reacceleration?

Giuliani, Cardillo et al. 2011
Cardillo et al. 2014

Ackermann et al. (2013)
Middle aged SNRs ($t \geq 10^4$ yrs) with a slow shock velocity ($v_s \sim 100$ km/s)

Interaction with a molecular cloud (high average density, $n \sim 200$ cm$^{-3}$) correlated with GeV (and TeV for IC443) gamma-ray emission

Correlation with only a fraction of the radio emission

Hadronic emission described by a broken power-law with a very steep high-energy spectral index
REACCELERATION OR ACCELERATION?

REACCELERATION

✧ Pre-existing Galactic CR protons & electrons
✧ Reacceleration $\rightarrow$ hardening of spectral indices steeper than $\alpha = (3r_{sh})/(r_{sh}-1)$
✧ Compression $\rightarrow$ higher energies, higher spectrum ($s = (n_2/n_0)/r_{sh}$)
✧ Energy losses pp/ionization & ioniz/synch/Brems/IC
✧ Low-energy cut off and Malkov steepening

ACCELERATION

✧ Freshly accelerated CRs with a spectral index $\alpha = (3r_{sh})/(r_{sh}-1)$
✧ Compression $\rightarrow$ higher energies, higher spectrum ($s = (n_2/n_0)/r_{sh}$)
✧ Energy losses
✧ Broken power–law with Malkov steepening

Crushed Cloud model (Blandford & Cowie 1982)

$\begin{align*}
\text{Galactic CRs} & : n_0, B_0 \\
\text{Reacceleration} & : n_1, B_1, r_{sh} \\
\text{Compression} & : n_2, B_2, s
\end{align*}$
**REACCELERATION: our model**

**Crushed Cloud model (Blandford & Cowie 1982)**

- Local Interstellar Spectrum from Voyager 1 (Potgieter 2013)
  \[\Rightarrow\] harder at low-energy: no need low-energy cut-off

- Hydrogen and Helium contribution with HE hardening.

- Adding also the only compressed Galactic component.

- Simple PL spectrum

- No steepening but HE cut-off

**Graph**

- Protons: LIS spectrum
- Electrons: LIS spectrum
- Protons: final
- Electrons: final

- \[B_0 = b \left( \frac{n_0}{1 \text{ cm}^{-3}} \right)^{1/2}\]
- \[n_m = 94 \ n_0 \ b \left( \frac{v_{sh}}{10^7 \text{ cm/s}} \right)\]
- \[B_m = (3/2)^{1/2} \left( \frac{n_m}{n_0} \right) B_0\]

**Cardillo, Amato, Blasi, in preparation**
**REACCELERATION: our model**

Maximum momentum

$$p_M = 8.7 \times 10^{-1} (B_0/1\,\mu G) \left( \frac{t_{int}}{10^4\,\text{yrs}} \right)^2 \left( \frac{L_c}{1\,\text{pc}} \right)^{-1} \left( \frac{v_{sh}}{10^7\,\text{cm/s}} \right)^4$$

Kraichnan diffusion

$$D(E) = \frac{1}{3} r_L c \left( \frac{k}{k_0} \right)^{1/2}$$

$$p_M \sim 21.5\,\text{GeV/c}$$

$$t_{int} \sim 1700\,\text{yrs} < t_{age}$$

$$r_{sh} = 3.72 \rightarrow \alpha = 2.1$$

$$n_2 \sim 10^4\,\text{cm}^{-3}, B_2 \sim 1\,\text{mG}$$

filling factor $f \sim 20\%$

$$L_c \sim 0.1\,\text{pc}$$

**Preliminary**

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Gamma-ray emission can be explained by the only reacceleration

→ upper limit for efficiency of possible CR acceleration

- Hydrogen and **Helium** galactic contribution with HE hardening

- **Simple PL** spectrum equal for electrons and protons

- Electron/proton ratio \( \kappa_{ep} \sim 10^{-2} \)

- **No steepening** but HE cut-off

\[
\begin{align*}
\text{Protons:injection} & \quad \text{Electrons:injection} \\
\text{Protons:final} & \quad \text{Electrons:final}
\end{align*}
\]

Cardillo, Amato, Blasi, in preparation
Maximum momentum
\[ p_M = 8.7 \times 10^{-1} \left( B_0 / 1 \mu G \right) \left( t_{\text{int}} / 10^4 \text{yrs} \right)^2 \left( L_c / 1 \text{pc} \right)^{-1} \left( v_{sh} / 10^7 \text{cm/s} \right)^4 \]

Kraichnan diffusion
\[ D(E) = 1/3 \ r_L c \ (k/k_0)^{1/2} \]

\[ p_M \approx 21.5 \text{ GeV/c} \]

\[ \xi_{\text{SCR}} \approx 10^{-4} \]

\[ t_{\text{int}} \approx 1700 \text{ yrs} < t_{\text{age}} \]
\[ r_{sh} = 3.72 \rightarrow \alpha = 2.1 \]
\[ n_2 \approx 10^4 \text{ cm}^{-3}, \ B_2 \approx 1 \text{ mG} \]
\[ \text{filling factor } f \approx 20\% \]
\[ L_c \approx 0.1 \text{ pc} \]

ACCELERATION: our model

NO BREAK!!

PRELIMINARY

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PRELIMINARY
(new results from VERITAS and Fermi, see Kumar poster and Hewitt talk)

Reacceleration

acceleration

NO BREAK!!
The evidence of CR presence in the middle-aged SNRs cannot imply acceleration with certainty.

Reacceleration and compression of pre-existing CRs can explain gamma-ray emission from W44 and IC443. Only upper limit for freshly accelerated CR efficiency.

In both reacceleration and acceleration case, we can explain gamma-ray emission with a simple power-law with a high-energy cut-off.

- No broken-power law distributions
- No very steep high-energy index

However, the spectral index is likely steeper than the value provided by linear and no-linear DSA theory.
Thank you very much!