The role of re-acceleration in the understanding of Cosmic-Ray direct and indirect data.

Martina Cardillo
INAF - IAPS
martina.cardillo@inaf.it

Madison (Wisconsin) July 30, 2019
Protons (85%)  
Nuclei (13%)  
Electrons/Positrons (2%)  

Solar modulation  
Power law $E^{-2.7}$  
$W_{CR} \sim 1 \text{ eV/cm}^3$  

CR "Knee"  
Power law $E^{-3.1}$  
CR "Ankle"  

GALACTIC  
Extra-GALACTIC

1 particle/m$^2$/s  
1 particle/m$^2$/yr  
1 particle/km$^2$/yr  
A few PeV
Where do they come from?
WHERE DO THEY COME FROM?

SUPERNOVA REMNANTS

- Energetics
- Possibility of energy gains by repeated shock crossing (1 order Fermi acceleration)
- Indirect Evidences (X-ray, Balmer Lines)

HOW CAN WE OBTAIN DIRECT EVIDENCES?

**GAMMA-RAY PHOTONS**

\[
\begin{align*}
p + p_{\text{target}} &\rightarrow p + p_{\text{target}} + \pi^0 \\
\pi^0 &\rightarrow \gamma + \gamma
\end{align*}
\]

- No deviations $\rightarrow$ source direction
- Same spectrum of primary protons
- $E_{\gamma,M} \approx 10\% E_{p,M}$
Low-Energies

Hadronic or Leptonic?

→ pion bump detection: distinction leptonic from hadronic component only at E<200 MeV

High-Energies

Pevatrons?

→ No young SNRs detected in the gamma-ray band with a spectrum up to E= 100 TeV

Acceleration: direct evidences

CAS A
Abdo et al. 2010

Tycho
Giordano et al. 2012
The breakthrough: W44

- Very bright radio middle aged Supernova Remnants
- Interaction with a molecular cloud (high average density, $n \sim 200 \text{ cm}^{-3}$)
- Fermi-LAT detected (low sensitivity at the lowest energies (Abdo et al. 2010))

Gamma-ray emission below 200 MeV detected, for the first time, by AGILE (Astro Rivelatore Gamma ad Immagini LEggero) from the SNR W44
The breakthrough: confirmation

• Presence of a broken PL and of a very steep HE spectral index
  → not expected from diffusive shock acceleration theory;

• The shock of middle-aged remnants are slow (vs < 100 km/s)
  → acceleration efficiency $\xi_{CR}$ has to be too high in order to explain the emission:
  $P_{CR} = \xi_{CR} \rho v_{sh}^2$
Acceleration vs Reacceleration

- Thermal Particle injection
  - micro-physics

- First order Fermi acceleration

- Injection Spectrum:
  - Power-law with index $\gamma_p$ due to shock compression ratio

- HE cut-off due to time and loss limitation

- Normalization proportional to $\xi_{CR} \rho v^2_{sh}$

- Pre-existing CR particles
  - from Voyager data

- First order Fermi acceleration

- Injection Spectrum:
  - if it is harder than $\gamma_p \rightarrow$ same of parent population
  - if steeper than $\gamma_p$, it hardens to $\gamma_p$

- HE cut-off due to time and loss limitation

- Normalization depending on shock compression ratio and on pre-existing CR normalization
Reacceleration of pre-existing CRs

- spectrum measured inside the heliosphere

Adiabatic Compression (crushed cloud, Blandford 1982)

- higher energies, higher normalization

Energy losses → (pp/ionization & ioniz/synch/Brems/IC)

Low-energy cut off, no losses, no secondaries and Malkov steepening
W44: Reacceleration – Last model

- Reacceleration of pre-existing Galactic CR from Voyager spectra OUTSIDE the heliosphere → VERY IS SPECTRUM
- Crushed Cloud Compression
- Secondary particles and low-efficiency accelerated CRs
- Simple PL with no steepening but HE cut-off due to the limited time (fully ionized pre-shock medium)

"IT CAN BE DONE!!!!"
**Diffusive Shock Re-acceleration: OB star wind**

- The nearest star Forming Region
- Distant from the Galactic Plane
- Embedded in the Orion–Eridanus Superbubble.

Estimation of $W_{CO} - N(H_2)$ conversion ratio $X_{CO}$:

$$N(H_2) = X_{CO} W(CO J = 1 \rightarrow 0) \text{cm}^{-2}$$

Gamma-ray excess from Fermi-LAT and AGILE at

$$(l,b) = [213.9, -19.5]$$

Possible explanations:

- **dark gas**: UV radiation at inner edge prevent CO formation
- **Non linearity** in the H2–CO relation (high star formation rate)
CRs: local acceleration/re-acceleration at k-Ori wind forward shock?

- Forward shock velocity very low (vs < 10 km/s)
- High interaction time → high losses

Cosmic Ray Re-Acceleration in correspondence of k-Ori wind forward shock can explain the AGILE spectrum and the lack of TeV and radio emission from that region.
Reacceleration: not only SNRs

- Hardening of secondary CR spectra above 300 GV of rigidity
- Oblique shock cannot accelerate particles

Reacceleration can explain secondary hardening:
- it hardens the secondary spectrum that follows the primary spectrum one
- it explains the B/C measurements of AMS-02

Reacceleration can provide a minimum level of magnetic field amplification for any SNR shock
- changing of the inclination angle
- injection
Conclusions

- We have the evidences that SNRs can energize Cosmic Ray particles
- All low-energy detected SNRs have gamma-ray spectra not easily explained with freshly accelerated CRs
- Diffusive shock Re-acceleration of pre-existing particles is always present if there are first order Fermi Acceleration conditions
- Particle Re-acceleration can explain middle-aged SNR (and other source) spectra and some features of secondary particle spectrum
- Whereas we keep looking for acceleration evidences, we must to take into account re-acceleration effects

We must avoid that "it is the theory which decides what can be observed"
Thank you very much!