PARTICLE ACCELERATION IN ASTROPHYSICAL SHOCKS AND THE ORIGIN OF COSMIC RAYS

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CR Acceleration at shocks

TEST PARTICLE DIFFUSIVE SHOCK ACCELERATION

- POWER LAW SPECTRA
- THE SLOPE IS ONLY DEPENDENT UPON THE COMPRESSION FACTOR AT THE SHOCK
- THE SPECTRUM FOR STRONG SHOCKS IS ASYMPTOTICALLY $E^{-2}$
- NO EASY WAY TO DETERMINE MAXIMUM ENERGY
- BUT WHEN ESTIMATED USING THE GALACTIC $D(E) \rightarrow E_{\text{MAX}} \sim \text{GeV}$
In general: $R_d > H >> h$

**ASSUMPTIONS:**
1. Instantaneous injection of particles in a point in the disc
2. Infinitely thin disc, $h \to 0$ and infinitely extended disc, $R_d \to \infty$
3. Free escape of the particles from above and below the halo $n(z = \pm H, r, E) = 0$

\[
n_{CR}(E) = \int_0^\infty d\tau \int_0^{R_d} dr 2\pi r \frac{N(E) R}{\pi R_d^2} \Im(z = 0, r = 0, x = y = 0) = \frac{N(E) R}{2\pi D(E) R_d} \frac{H}{R_d}
\]
The Supernova remnant paradigm in numbers

Let us assume that the rate of SN in the Galaxy is \( R \) and each produces a power law spectrum of protons \( N(E) = K (E/E_0)^{-\gamma} \) and we take \( E_0 \sim m \sim 1 \) GeV

\[
E_{CR} = \int dE N(E)E = \frac{K}{\gamma - 2} = \xi_{CR}E_{SN} \Rightarrow K = (\gamma - 2)\xi_{CR}E_{SN}
\]

and energies are taken to be normalized to \( E_0 \).

The observed spectrum of protons at Earth is and taking \( D(E) \sim (\rho/3GV)^{\delta} \) where \( \rho \) is the rigidity

\[
\phi(E) = c \eta_{CR}(E)/(4\pi)
\]

\[
\phi_{CR}(E) \approx 2.4E_{51}\xi_{CR}R_{d,15}^{-2}R_{SN,30}(\gamma - 2)3^{\delta}E_{TeV}^{-2.73}TeV^{-1}m^{-2}s^{-1}sr^{-1}
\]

and comparing with the observed spectrum

\[
8.7 \times 10^{-2}E_{TeV}^{-2.73}TeV^{-1}m^{-2}s^{-1}sr^{-1}
\]

\( \xi_{CR} \sim 7\% \) for \( \delta = 1/3 \)

\( \xi_{CR} \sim 11\% \) for \( \delta = 0.54 \)

\( \xi_{CR} \sim 58\% \) for \( \delta = 0.7 \)

Relatively large efficiencies required
BEYOND TEST PARTICLES: \textit{Non linear} DSA

Malkov, Berezhko & Voelk, Ellison et al, PB, Amato & PB...

- Non linear Theory
- Dynamical Reaction of Accelerated Particles
- CR Induced B-field Amplification
- Dynamical Reaction of Amplified B-fields

Cosmic ray acceleration up to The knee
Dynamical Reaction of Accelerated Particles

Conservation of Mass, Momentum and Energy +

\[
\frac{\partial f}{\partial t} = \frac{\partial}{\partial x} \left[ D \frac{\partial f}{\partial x} \right] - u \frac{\partial f}{\partial x} + \frac{1}{3} \frac{du}{dx} p \frac{\partial f}{\partial p} + Q(x,p,t)
\]

Transport equation for cosmic rays
SHOCK HEATING and SPECTRA

\[
\left( \frac{p}{mc} \right)^4 \frac{f(p)}{n_0} (mc)^3
\]

- REDUCED HEATING
  - \( u_0 = 5 \times 10^8 \text{ cm/s} \)
  - \( \xi = 3.5 \)
  - \( \frac{p_{\text{max}}}{mc} = 10^5 \)

- SHOCK MODIFICATION

PB, Gabici & Vannoni 2005
COSMIC RAY INDUCED MAGNETIC FIELD AMPLIFICATION

**RESONANT GROWTH** (Bell 78, Skilling 75, Lagage & Cesarsky 83)

Alfven waves grow in resonance with diffusing particles which resonantly scatter on them (growth and scattering are naturally on the same scale)

**NON-RESONANT GROWTH**

Bell 04 discussed a non resonant way to grow (non-Alfvenic) waves with $\lambda \ll$gyration radius $\rightarrow$ no efficient scattering unless inverse cascade

Other instabilities (e.g. firehose) lead to $\lambda \gg$gyration radius (still non resonant)
SMALL PERTURBATIONS IN THE LOCAL B-FIELD CAN BE AMPLIFIED BY THE SUPER-ALFVENIC STREAMING OF THE ACCELERATED PARTICLES.

Particles are accelerated because there is a high magnetic field in the acceleration region.

High magnetic field is present because particles are accelerated efficiently.

Without this non-linear process, no acceleration of CR to high energies (and especially not to the knee!)
Successes of the SNR paradigm

1. Observation of X-ray rims

TYPICAL THICKNESS OF FILAMENTS: $\sim 10^{-2}$ pc

The synchrotron limited thickness is:

$$\Delta x \approx \sqrt{D(E_{\text{max}}) \tau_{\text{loss}}(E_{\text{max}})} \approx 0.04 \ B_{100}^{-3/2} \text{pc}.$$  

$B \approx 100$ $\mu$Gauss

$$E_{\text{max}} \approx 10 \ B_{100}^{-1/2} u_8 \text{ TeV}$$

$$\nu_{\text{max}} \approx 0.2 \ u_8^2 \text{ keV}$$

In some cases the strong fields are confirmed by time variability of X-rays

Uchiyama & Aharonian, 2007
Successes of the SNR paradigm

2. Max energy and the knee

Magnetic field amplification leads to higher values of the Maximum energy

Data from Bertaina et al. 2008

PB, Amato & Caprioli, 2007
Successes of the SNR paradigm

3. evidence for a CR precursor?

Molino, Amato, PB & Caprioli 2010
Successes of the SNR paradigm

4. Balmer dominated shocks

**DOWNSTREAM**

ION Temperature LOWER because of CR acceleration

NEUTRAL Temperature HIGHER because of charge exchange

BROAD BALMER LINE IS NARROWER

NARROW BALMER LINE IS WIDER
OBSERVATIONS OF BALMER DOMINATED SHOCKS

\[ W_{\text{broad}} = 1100 \pm 63 \text{ km/s} \rightarrow T_2 = 2.3 \pm 0.3 \text{ keV} \]

Shock speed from proper motion

\[ v_{\text{shock}} = 6000 \pm 2800 \text{ km/s} \left( \frac{d}{2.5 \pm 0.5 \text{ kpc}} \right) \left( \frac{\dot{\theta}_{\text{obs}}}{0.5 \pm 0.2'' \text{ yr}^{-1}} \right) \rightarrow T_2 = 20 - 150 \text{ keV (no equilibration)} \]

12 - 90 \text{ keV (equilibration)}

Helder et al. 2009

INFERRED EFFICIENCY of CR ACCELERATION 50-60% !!!
OBSERVATION OF BALMER DOMINATED SHOCKS

broader narrow Balmer line

Sollerman et al. 2003

<table>
<thead>
<tr>
<th>SNR</th>
<th>Shock velocity (km s(^{-1}))</th>
<th>Narrow component FWHM (km s(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cygnus Loop</td>
<td>300–400</td>
<td>28–35</td>
</tr>
<tr>
<td>RCW 86 SW</td>
<td>580–660</td>
<td>32 ± 2</td>
</tr>
<tr>
<td>RCW 86 W</td>
<td>580–660</td>
<td>32 ± 5</td>
</tr>
<tr>
<td>RCW 86 NW</td>
<td>580–660</td>
<td>40 ± 2</td>
</tr>
<tr>
<td>Kepler D49 &amp; D50</td>
<td>2000–2500</td>
<td>42 ± 3</td>
</tr>
<tr>
<td>0505-67.9</td>
<td>440–880</td>
<td>32–43</td>
</tr>
<tr>
<td>0548-70.4</td>
<td>700–950</td>
<td>32–58</td>
</tr>
<tr>
<td>0519-69.0</td>
<td>1100–1500</td>
<td>39–42</td>
</tr>
<tr>
<td>0509-67.5</td>
<td>–</td>
<td>25–31</td>
</tr>
<tr>
<td>Tycho</td>
<td>1940–2300</td>
<td>44 ± 4</td>
</tr>
<tr>
<td>SN 1006</td>
<td>2890 ± 100</td>
<td>21 ± 3</td>
</tr>
</tbody>
</table>

Broadening of the narrow line hints to a mechanism for heating of the neutrals upstream on scales shorter than ionization scales. TURBULENT HEATING CHARGE EXCHANGE UPSTREAM

\[ W_n \sim 30–50 \text{ km/s} \rightarrow T \sim 2–6 \times 10^4 \text{ K} \]
Observation of Balmer dominated shocks:
Possible evidence for a CR precursor in the narrow Balmer line

A broadened narrow Hα line from upstream shows that the neutrals and ions have some level of charge exchange $\rightarrow$ different bulk velocities and/or $T$’s between the two components $\rightarrow$ CR precursor
Gamma Rays
1. e/p Equilibration downstream? (Morlino et al. 2009)
2. Very low value of $K_{ep}$ at given time
3. Lines from non-equilibrium ionization? (Ellison et al. 2010)
4. What are those Fermi data points telling us?
W44 – an old SNR

Age: 20kyrs

Slope: ~3 !!!
IC443 – possible interaction with a mc

Slope: 2.6

Age very uncertain: 2 kyr-30 kyr
Most SNR detected by Fermi have relatively steep spectra (some exceptions, such as RXJ1713)

The predicted spectra would naively require steep diffusion $D(E) \sim E^{0.7}$ in conflict with anisotropy measurements
A small print in the theory of DSA?: a point as important as poorly known

\[
\tilde{u}(x) \frac{\partial f_i(x,p)}{\partial x} = \frac{\partial}{\partial x} \left[ D_i(x,p) \frac{\partial f_i(x,p)}{\partial x} \right] + \frac{p}{3} \frac{d\tilde{u}(x)}{dx} \frac{\partial f_i(x,p)}{\partial p} + Q_i(x,p)
\]

Velocity of scattering centers in the shock frame NOT velocity of the plasma

In general the velocity of scattering centers is small and there is no problem

BUT AMPLIFIED MAGNETIC FIELD \( \rightarrow \) high velocity ???

\[
v_w = \frac{\delta B}{\sqrt{4\pi \rho}} \gg v_{A,0}
\]

VERY MACROSCOPIC CONSEQUENCES ON SPECTRA!
ROLE OF NUCLEI: The knee

Caprioli, PB, Amato 2010
WHERE DO GALACTIC CR end?

1. The SNR paradigm hints to a galactic CR spectrum ending at $\sim a$ few $10^{17}$ eV

2. Observations of chemical composition also suggest the same trend
Anisotropy of Galactic CR

$\delta = 0.7$  
Required Efficiency: ~ 50-60%

Blasi 2010
Anisotropy of Galactic CR

$\delta = 0.55$  

Required Efficiency: $\sim 10\%-15\%$

Blasi 2010
Anisotropy of Galactic CR

\[ \delta = \frac{1}{3} \]

Required Efficiency: \(~ 5-10\%\)

Blasi 2010
Conclusions

1. Non-linear DSA in (some) SNRs is reliably observed

2. The SNR paradigm collects much circumstantial evidence

3. But some problems remain open
   a. Steep gamma ray spectra
   b. NLDSA predicts flat spectra unless $v_W$ large
   c. Even in this case NLDSA leads to require $\delta=0.55$
   d. Anisotropy still seems problematic

4. Note of caution n. 1: what we see at the Earth is a complex overlap of many factors

5. Note of caution n. 2: SNR of type II, the most frequent, are also the ones which are harder to observe in gamma rays (low density)