Cosmic ray acceleration and transport from MeV energies to the knee

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Voyager 1 at the edge of interstellar space

launched in 1977, 70 kb, 22 w

Voyager 1 – 124 AU; 18.6 billion km
Power all instruments until 2020 – 150 AU
Turn off final instrument in 2025

Voyager 2 – 102 AU; 15.2 billion km

Heliosheath
Termination Shock

Heliosphere

after E. Stone 2013

direct measurements of interstellar CR spectra at low energies

low energies: Voyager 1
Stone et al. 2013

high energies: BESS
Pamela
Sparvoli et al 2012

H
He

power law

From outside:
- GCR protons >70 MeV
- GCR electrons 7 to ~100 MeV

From inside:
- ACR protons 7 to 60 MeV
- TSPs 0.5 to 30 MeV

Day of 2012
$J_{cr}(E) = Q_{cr}(E) \times T_{e}(E)$

source power confinement time of CR in the Galaxy:
$\sim 10^8$ yr at 1 GeV

$\nu_{sn} = (30 \text{ yr})^{-1}$

$\sim 15\%$ of SN kinetic energy transfer to cosmic rays

Ginzburg & Syrovatsky 1964

traversed matter thickness $\sim 12 \text{ g/cm}^2$ at 1 GeV/nuc

(surface gas density of galactic disk $\sim 2.5 \times 10^{-3} \text{ g/cm}^2$)
basic empirical diffusion model


empirical diffusion coefficient

\[ D \sim 3 \times 10^{28} \text{ cm}^2 / \text{s} \quad \text{at 1 GeV/n} \]

diffusion mean free path

\[ l \sim 1 \text{ pc} \]

NGC4631

H = 4 kpc, R = 20 kpc

\[ D \times l = \frac{1}{3} \text{ GeV} \cdot \text{cm}^2 / \text{s} \]

\[ \frac{B}{C} \sim 0.35 \quad \Phi = 500 \text{ MV} \]
**mechanism of cosmic ray diffusion**

\[ r_g = \frac{1}{k} \text{ - resonance condition} \]

\[ D_{\parallel} \approx \frac{\nu r_g}{3} \cdot \frac{B_{\text{tot}}^2}{B_{\text{res}}^2} \]

Jokipii 1966, ...

Cosmic ray particles are strongly magnetized but large-scale random magnetic field \((L_{\text{max}} \sim 100 \text{ pc})\) makes diffusion close to isotropic.

**spectrum of turbulence**

\[ B_{\text{res}}^2 = \int_{k_{\text{res}}} w(k) dk \]

\[ w(k) dk \sim k^{-2+a} dk, \quad D_{\parallel} \sim \nu r_g^a \]

- \(a = 1/3\) Kolmogorov spectrum
- \(a = 1/2\) Kraichnan spectrum
- \(a = 0\) random discontinuities
- \(a = 1\) white noise (leads to Bohm diffusion scaling \((D_B = \nu r_g/3)\)
**regimes of cosmic ray diffusion**

**Kolmogorov spectrum:** $D \sim vR^{1/3} +$ reacceleration
- may be valid up to $10^{17}Z$ eV
- source spectrum $R^{-2.4}$ - too soft to be produced in SNRs
  (but dispersion of SNR parameters may help)
- anisotropy - acceptable
- peak of B/C ratio at 1 GeV/n - explained by distributed reacceleration
- underpredicts antiproton flux below few GeV
- in contradiction with theory of MHD turbulence (wave distribution in k-space)
- contradiction to radio-astronomical data? (too many secondary leptons)

**Kraichnan spectrum:** $D \sim vR^{1/2} +$ wave damping
- may be valid up to $10^{16}Z$ eV only
- source spectrum $R^{-2.2}$ - consistent with shock acceleration in SNRs
- anisotropy - too high
- peak of B/C ratio at 1 GeV/n - explained by turbulence dissipation on CR
- B/C ratio at V1 energies is too high
- not in contradiction with theory of MHD turbulence -
**diffusion-convection model: galactic wind driven by CR**


**CR scale height is larger than the scale height of thermal gas. CR pressure gradient drives the wind.**

+ **cosmic ray streaming instability with nonlinear saturation**


\[ D \sim \frac{vB}{q_{cr}} \left( \frac{p}{Zm_p c} \right)^{\gamma_s - 1} \approx 10^{27} \beta \left( \frac{p}{Zm_p c} \right)^{1.1} \text{ cm}^2 / \text{s}, \]

\[ \gamma = \frac{3\gamma_s - 1}{2} \approx 2.7, \quad \text{at} \quad \gamma_s \approx 2.1 \]

\[ X \sim \frac{H_{\text{eff}}}{D} \sim \left( \frac{p}{Zm_p c} \right)^{\gamma_s - 1/2} \approx \left( \frac{p}{Z} \right)^{-0.55} \]
**diffusive shock acceleration**

Fermi 1949, Krymsky 1977, Bell 1978, ...

\[ J \sim p^{-\gamma_s}, \quad \gamma_s = \frac{\sigma + 2}{\sigma - 1} = 2 \]

for test particles!

Compression ratio = 4

\[ \frac{u_{sh} R_{sh}}{D(p)} > 10 \]

-condition of CR acceleration and confinement

- \( D(p) \) should be anomalously small both upstream and downstream; CR streaming creates turbulence in shock precursor

Bell 1978; Lagage & Cesarsky 1983; McKenzie & Völk 1982 ...

“Bohm” limit \( D_B = \frac{v_r g}{3} \):

\[ E_{max} \approx 0.3 \cdot Z e \cdot \frac{u_{sh}}{c} \cdot B \cdot R_{sh} \]

\[ E_{max,ism} = 10^{13} \ldots 10^{14} Z \text{ eV} \]

for \( B_{ism} = 5 \times 10^{-6} \text{ G} \)

\[ \sim B_{sh} t^{-1/5} \] at Sedov stage
abandonment of interstellar Bohm limit hypotheses;
\[ D \approx D_{B,\text{ism}} \]

- strong cosmic-ray streaming instability gives
\[ \delta B \gg B_{\text{ism}} \text{ in young SNR} \]
Bell & Lucek 2000, Bell 2004
Pelletier et al 2006; Amato & Blasi 2006; Zirkashvili & VP 2008; Vladimirov et al 2009;
Gargate & Spitkovsky 2011

under extreme conditions (SN Ib/c, e.g. SN1998 bw)

\[ E_{\text{max}} \sim 10^{17} Z \left( u_{sh}/3 \times 10^4 \text{ km/s} \right)^2 M_{ej}^{1/3} n^{1/6} \text{ eV} \]
\[ B_{\text{max}} \sim 10^{-3} \left( u_{sh}/3 \times 10^4 \text{ km/s} \right) n^{1/2} \text{ G} \]

confirmed by X-ray observations of young SNRs
SN 1006, Cas A, Tycho, RCW 86, Kepler, RX J1713.7-3946, Vela Jr., G1.9+0.3

\[ B^2/8\pi = 0.035 \mu u^2 /2 \]
Voelk et al. 2005

- wave dissipation in shock precursor leads to rapid decrease of \( \delta B \) and \( E_{\text{max}} \) with time

VP & Zirakashvili 2003

- finite \( V_a \) leads to steeper CR spectrum

\[ \sigma = \frac{u_1 - V_{a,1}}{u_2 + V_{a,2}} \]
numerical simulations of particle acceleration and radiation in SNR

Zirakashvili & VP 2012,
semianalytic models Blasi et al.(2005), Ellison et al. (2010)

radio polarization in red (VLA),
X-rays in green (CHANDRA),
optical in blue (HST)

Fig. 6.— The broad-band spectral energy distribution of nonthermal radiation of Cas A calculated within the hadronic model H1. The following radiation processes are taken into account: synchrotron radiation of accelerated electrons (solid curve on the left), IC emission (dashed line), gamma-ray emission from pion decay (solid line on the right), thermal bremsstrahlung (dotted line on the left), nonthermal bremsstrahlung (dotted line on the right). Experimental data in gamma-ray (Fermi LAT, present work); VERITAS, Acero et al. 2010, data with error-bars) and radio-bands (Baars 1977, circles), as well as the power-law approximation of Suzaku X-ray data (Maeda et al. 2009, diamonds) from the whole remnant are also shown.
calculated spectrum of Galactic cosmic rays: acceleration in SNRs, transport in interstellar magnetic fields, $D \sim R^{0.54}$

VP, Zirakashvili, Seo 2010

«knee» is formed at the beginning of Sedov stage

$$E_{knee}/Z = 1.1 \times 10^{15} W_{sn,51} n^{1/6} M_{ej}^{2/3} \text{ eV},$$

$$E_{knee} c/Z = 8.4 \times 10^{15} W_{sn,51} \sqrt{M_{-5}/u_{w,6}} M^{-1}_e \text{ eV}$$
knee and beyond

structure above the knee

different types of nuclei, $E_{\text{knee}} \sim Z$

different types of SN

transition to extragalactic component
features to explain:

hardening above 200 GeV/nucleon
concave source spectrum
superposition of sources
new source Zatsepin & Sokolskaya 2006
reacceleration in local bubble Erlykin & Wolfendale 2011
streaming instability below 200 GV Blasi et al. 2012

spectra of p and He are different
shock goes through material enriched in He:
- helium wind VP et al. 2010,
- bubble Ohira & Ioka 2011
effect of injection Malkov et al 2011
both features
contribution of reversed SNR shock VP et al 2013

BUT!
preliminary
AMS-02
data do not show spectral features
positrons in cosmic rays

GALPROP calculations Cholis, Hooper 2014

\[ H = 4 \text{ kpc} \]
\[ D = 2.95 \times 10^{28} v(R/3 \text{ GV})^{0.43} \text{ cm}^2/\text{s} \]
\[ V_a = 10 \text{ km/s} \]


e+ production and acceleration in shell SNRs Blasi 2009, Berezhko, Ksenofontov 2013

reverse shock in radioactive ejecta Ellison et al 1990, Zirakashvili, Aharonian 2011

annihilation and decay of dark matter Tylka 1989, Fan et al 2011
large-scale anisotropy

global distribution of SNRs
local SNRs < 1 kpc, no Vela Jr
knee on rigidity in the sources
isotropic diffusion, H = 4 kpc
all groups of nuclei

data:
Conclusions

Cosmic ray origin scenario where supernova remnants serve as principle accelerators of cosmic rays in the Galaxy is strongly confirmed by recent numerical simulations.

Diffusion model provides reasonably good description of cosmic ray propagation in the Galaxy even under simplified assumptions on cosmic ray transport coefficients and geometry of propagation region (e.g. as included in GALPROP code). Energy dependence of diffusion is still uncertain.

High-accuracy measurements indicate deviations of cosmic ray spectra from plain power laws below the knee. If confirmed, it requires refining models of cosmic ray acceleration and propagation.