Origin of cosmic rays

Vladimir Ptuskin

IZMIRAN Russia/University of Maryland USA

FFP14, Marseille
Outline

• Introduction
• Voyager 1 at the edge of interstellar space
• Cosmic ray transport in the Galaxy
• Supernova remnants – main Galactic accelerators
• Positrons in cosmic rays
• Structure of the “knee”
• Energy limit for galactic sources
• Extragalactic cosmic rays: transport and sources
• High energy neutrinos of cosmic origin
A

\[ N_{\text{cr}} = 10^{-10} \text{ cm}^{-3} \] - total number density in the Galaxy

\[ \omega_{\text{cr}} = 1.5 \text{ eV/cm}^3 \] - energy density

\[ E_{\text{max}} = 3 \times 10^{20} \text{ eV} \] - max. detected energy

\[ Q_{\text{cr}} = 10^{41} \text{ erg/s} \] - power of Galactic CR sources

\[ A_1 \sim 10^{-3} \] - dipole anisotropy at 1 – 100 TeV

\[ r_g \sim 1 \times \text{E}/(Z \times 3 \times 10^{15} \text{ eV}) \text{ pc} \] - Larmor radius at B=3x10^{-6} G
Voyager 1 at the edge of interstellar space

Launched in 1977, 70 kb, 22 w

Voyager 1 – 124 AU; 18.6 billion km
Voyager 2 – 102 AU; 15.2 billion km
Heliosphere

Power all instruments until 2020 – 150 AU
Turn off final instrument in 2025

low energies: Voyager 1
Stone et al. 2013

high energies: BESS
Pamela
Sparvoli et al. 2012

direct measurements of interstellar CR spectra at low energies

Energy, MeV/nuc

Particle (/m^2 sec sr MeV/nuc)

10^-5
10^-4
10^-3
10^-2
10^-1
10^0
10^1
10^2
10^3
boundary

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
"Golden age" of new CR measurements

Spacecrafts:
Voyagers; ACE, Pamela, Fermi/LAT, AMS

Balloons:
BESS, CREAM, TRACER

Cherenkov telescopes:
HESS, MAGIC, VERITAS

EAS detectors:
KASCADE-Grande, MILAGRO, ARGO-YBJ, TUNKA, EAS-TOP, IceCube/IceTop, Auger, Telescope Array
energy balance: \( \sim 15\% \) of SN kinetic energy go to cosmic rays to maintain observed cosmic ray density

Ginzburg & Syrovatskii 1964

steady state: (without energy losses and nuclear fragmentation)

\[ J_{cr}(E) = Q_{cr}(E) \times T(E) \]

source term, SNR

two power laws!

\[ E^{-2.1} \times E^{-0.6} \]

escape time from the Galaxy, \( 10^8 \) yr at 1 GeV, resonant scattering in random magnetic field \( 1/k_{res} = r_g \)

traversed matter thickness \( X \sim 12 \text{ g/cm}^2 \) at 1 GeV/nuc (surface gas density of galactic disk \( \sim 2.5 \times 10^{-3} \text{ g/cm}^2 \))
galactic wind driven by cosmic rays

\[ u_{\text{inf}} = 500 \text{km/s} \quad R_{\text{sh}} = 300 \text{kpc} \]

Ipavich 1975, Breitschwerdt et al. 1991, 1993

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


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

\[ \gamma = (3\gamma_s - 1) / 2 \approx 2.7, \text{ at } \gamma_s \approx 2.1 \]

\[ X \sim \frac{H_{\text{eff}}}{D} \sim \left( \frac{p}{Zm_p c} \right)^{\gamma_s - 1} \sim \left( \frac{p}{Z} \right)^{-0.55} \]
**why power law?**

Fermi 1949, 1954

\[ \delta p \approx \alpha p, \quad \alpha \approx \frac{u}{v} \quad \text{or} \quad \left( \frac{u}{v} \right)^2 \quad \text{- 1st or 2nd order acceleration} \]

approximate **Fermi formula** for \( J(E) = p^2 f(p) \propto p^{-\gamma} \):

\[ \gamma = 1 + \frac{\tau_a}{\tau_l} \]

**diffusive shock acceleration**

\[ \tau_a \sim 3 \frac{\ldots}{u_1 - u_2}, \quad \tau_l \sim \frac{\ldots}{u_2} \]

\[ \gamma = 1 + \frac{3}{r - 1} = 2 \]

at compression ratio \( r = \frac{u_1}{u_2} = 4 \)

Krymsky 1977, Bell 1978, …
$\frac{u_{sh} R_{sh}}{D(p)} > 10$ - condition of 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 ...

"Bohm" limit $D_B = \frac{\nu r}{3}$: $E_{\max} \approx 0.3 \cdot Z e \cdot \frac{u_{sh}}{c} \cdot B \cdot R_{sh}$

$E_{\max, ism} = 10^{13} \ldots 10^{14} Z \text{ eV}$ for $B_{ism} = 5 \times 10^{-6} \text{ G}$

Streaming instability gives $B \gg B_{ism}$ in young SNR


confirmed by X-ray observations SN 1006, Cas A, RCW 86, RX J1713.7-3946

under extreme conditions (e.g. SN1998 bw): $E_{\max} \sim 10^{17} Z \text{ eV}, \ B_{\max} \sim 10^{-3} \text{ G}$
numerical simulations of particle acceleration and radiation in SNR


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

Cas A

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 right), nonthermal bremsstrahlung (dotted line on the left). 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:

VP, Zirakashvili, Seo 2010

source spectra produced by SNRs

\[ \nu_{sn} \frac{4\pi c p^4 \Phi(p)}{E_{sn}} \]

protons

hydrodynamic eqs. + \( P_{cr} \); diffusion-convection transport eq. for CR with Alfvénic drift

«knee» is formed at the beginning of Sedov stage

\[ E_{knee}/Z = 1.1 \times 10^{15} W_{sn,51} n^{1/6} M_{ej}^{-2/3} \text{ eV} \]
positrons in cosmic rays; pulsars, dark matter, ...
**knee and beyond**

structure above the knee

different types of nuclei, $E_{\text{knee}} \sim Z$
different types of SN
transition to extragalactic component
\[ r_g = 1 \times \frac{E_{\text{EeV}}}{Z \times B_{\mu G}} \text{ Kpc} \]

\[ J \times E^{2.75} \]

Knee

GZK suppression?

\[ \langle \ln A \rangle \]
energy loss of ultra-high energy cosmic rays

- pair production: \( p\gamma \rightarrow p\, e^+e^- \)
- pion production: \( p\gamma \rightarrow N\, \pi \)

**GZK cutoff** at \( E_{\text{GZK}} \sim 6 \times 10^{19} \text{ eV} \)

Greisen 1966; Zatsepin & Kuzmin 1966

- photodisintegration of nuclei
  Stecker 1969

- Universe expansion
  \[-(1/E)\, (dE/dt)_{\text{adiabatic}} = H\]

\( H_0 = 100h \text{ km/(s Mpc)}, \ h = 0.71 \)
extragalactic sources of cosmic rays

desired in CR at E > 10^{19.5} eV

<table>
<thead>
<tr>
<th></th>
<th>SN</th>
<th>AGN jets</th>
<th>GRB</th>
<th>newly born fast pulsars (&lt; 5ms)</th>
<th>accretion on galaxy clusters</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 × 10^{-4} (Auger)</td>
<td>3 × 10^{-1}</td>
<td>3</td>
<td>3 × 10^{-4}</td>
<td>10^{-3}</td>
<td>10</td>
</tr>
<tr>
<td>8 × 10^{-3} for E &gt; 10^{9} eV</td>
<td>L_{kin} &gt; 10^{44} erg/s</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[ E_{max} \approx 10^{20} \times Z \times \beta^{1/2} \times \left( \frac{L_{jet}}{10^{45} \text{ erg/s}} \right)^{1/2} \text{ eV} \]


\[ E_{max} \approx 10^{19} \times Z \times \left( \frac{\Omega}{10^{4} \text{ sec}} \right)^{2} \text{ eV} \]

Auger
- transition to heavy elements above $10^{19}$ eV
- anisotropy

TA+HiRes
- proton dominated composition
- no significant anisotropy (?)

for heavy composition: $E_{\text{max}}/Z = 4 \times 10^{18}$ eV

easier to accelerate cosmic rays but difficult to identify their sources;
production of neutrinos is suppressed (Berezinsky - “disappointing” model)
very high energy neutrinos of cosmic origin

IceCube neutrino detector

3-year data:
excess of 37 neutrinos
above atmospheric
background (>5.7 sigma) at
3.10^{13} to 2.10^{15} eV

- cosmic neutrino flux per flavor with possible suppression above 2 PeV;
- equal flavor ratio 1:1:1;
- isotropic sky distribution

\[ E_v^2 \left( \frac{dN}{dE_v} \right) = (0.95 \pm 0.3) \times 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \]
neutrino production in cosmos is possible via interactions $p\gamma, pp(n)$ and decay chains
$\pi^+ \rightarrow \mu^+ \nu_\mu, \mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$

plus neutrino oscillations

- Galactic sources may account only for a minority of events
- cosmogenic (GZK) neutrino production is inefficient
- can be produced in extragalactic sources of UHE cosmic rays; not in GRB

WB bound? Waxman & Bahcall 1999
some coming projects

**JEM–EUSO** (2016, Extreme Universe Observatory, > 3 \(10^{19}\) eV, > 100000 km\(^2\) from space, instantaneous aperture ~100 PAO)

**LHAASO** (2013-2018, Large High Altitude Air Shower Observatory, Tibet 4300 m, gamma-rays and CRs till the knee and 1 EeV, 1 km\(^2\) array of electron and muon detectors for gamma rays > 30 TeV, 90000 m\(^2\) water Cherenkov detector array for gamma rays >100 GeV, 24 wide field Cherenkov telescopes and 5000 m\(^2\) shower core detectors for CRs > 30 TeV)

**CTA** (2018, Cherenkov Telescope Array, 100 GeV – 100 TeV, 100 telescopes ( 5m to 23 m diameter); two arrays to cover full sky; 10 times better sensitivity makes about 200 SNRs visible)

**Tunka–HiSCORE** (wide-angle Cherenkov gamma observatory, 1-100 km\(^2\), search for PeVatrons, \(E_{cr} =10^{14} – 10^{18}\) eV)

**CALET** (2014, scintillation calorimeter on ISS, e+ e- up to 20 TeV)

**ISS–CREAM** (2015, on ISS by Space-X)
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.

Accurate data on cosmic rays in the energy range $10^{17}$ to $10^{19}$ eV, where the transition from Galactic to extragalactic component occurs are becoming available.

Eliminating the uncertainties with energy spectrum and composition is necessary for understanding of cosmic ray origin at the highest energies.