"Energetic particles acceleration in planet magnetospheres and in the Galaxy: unsolved problems"

Mikhail Panasyuk
Skobeltsyn Institute of Nuclear Physics of Lomonosov Moscow State University

“Plasma in Astrophysics and in the Laboratory: the Ignitor Challenge”
Round table in the Italian Embassy, 20-22 June, 2011
Energy spectra of cosmic rays (solar maximum)

- Solar wind (H)
- Trapped radiation – Earth’s radiation belts
- Solar energetic particles (H)
- Galactic cosmic rays (H)

NOT SCALED

Log E (eV/nucl)

- 1 keV/n
- 1 MeV
- 1 GeV
- 1 TeV

Log I

10

0
CR astrophysics main problems

Sources?

-Accelerators?
All particles energy spectrum of CR
Supernovae

Energy balance
Ginzburg & Syrovatskii 1964

~ 15% of SN kinetic energy should go to cosmic rays to maintain observed $w_{cr}$

at $W_{sn} = 10^{51}$ erg, $v_{sn} = 1/(30$ yr)
Standard Model of Cosmic Ray Acceleration

**Accelerated particles**

**E_{\text{max}} \sim \text{BLZ} \approx 10^{14} \text{Z eV}

**Diffusive shock acceleration**

Fermi 1949, Krymsky 1977, Bell 1978, ...
Völk et al. magnetic field amplification in Tycho and other shell-type SNRs

\[ B \sim 300 \, \mu G, \text{ for Tycho’s SNR} \]

consistent with synchrotron spectrum from acceleration theory

Similar amplification in all other SNRs where such data are available: Cas A, SN 1006, Tycho, RCW 86, Kepler, RX J1713.7-3946, Vela Jr

very strong magnetic field in young SNRs is indirect but strong evidence of proton acceleration
Standard Model of Cosmic Ray Acceleration

Accelerated particles

Shock wave

Diffusive shock acceleration

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

$E_{\text{max}} \sim \text{BLZ} \approx 10^{17} \text{ eV}$
CR astrophysics main problems

Sources?

-Accelerators?

Mass composition of CR is the key for answer on this questions
CR nuclei spectra

COSMIC RAY ENERGY SPECTRUM

MSU array
Khrustiansen et al.
knee at $3 \times 10^{15}$ eV

EAS method

Yakutsk, Haverah Park, HiRes
AGASA, Auger - ankle at $3 \times 10^{15}$ eV

Greisen-Zatsepin
Kuzmin cut off?

HE CR Balloons Satellites

HE CR
On ground installations
Chemical composition around 10*15 eV have to be changed because of consequences of the acceleration model:

$$E \sim Z$$
Energy spectrum of CR
CR nuclei spectra below the knee

The knee

Spectra with the same slope?
Average mass definition below “the knee” – the real test for current models
CR chemical composition & SN acceleration models

Berezhko
Proton and helium spectra and the multiplicity of types of cosmic ray sources

Spectra for energy per particle

![Graph showing proton and helium spectra for energy per particle. The graph includes data points from AMS, CAPRI CE98, BESS-TeV, and ATIC.]
Beyond the 10*15 eV
Energy spectrum of CR
Mean mass composition dependence show enrichment by heavy ions.
Beyond the $10^{17}$ eV
Chemical composition become more lighter beyond $10^{17}$ eV?

NEW sources?
So,

- **Up to $10^{17}$ eV** – the transition region from light elements to heavier ones

- **Beyond $10^{17}$ eV** - the transition from heavier elements to light ones, or from galactic sources to extragalactic ones…

![Graph showing energy distribution with LHC energy indicated](image-url)
Instead of conclusions -

- Have we found the transition region between galactic and extragalactic sources already?

- Have we observed the LIMIT OF POWER of Galactic Accelerator equal to \( \sim 10^{15}Z \)?

- What kind of accelerators are responsible for the origin of particles at \( 10^{17} \text{ eV} \)?
Do we know other shocks in the Universe?
SEP’s acceleration by interplanetary shock waves
What is the efficiency of the CME to accelerate particles?
Acceleration of SEP during propagation

CME acceleration

Fermi acceleration

$V_s = 100 \div 1000 \text{ km/s}$

$E \approx 10^{31} \text{ erg}$

Berezhko (1999): ions energy up GeV
If these SEPs are accelerated by CME-driven shocks, they use a significant fraction of the shock kinetic energy (~3% to 20%)
Energy range of SEP: spectra

- direct measurements from space
- indirect measurements using geomagnetic cutoff
- NM and EAS arrays measurements on ground during GLE
SEP spectra from cutoff (sat. data)

Coronas – F data

Up to 10 GeV!
The question “does a shock wave propagating in the Corona accelerate particles up to ultra-relativistic energies “ is being discussed
Relativistic protons

X-ray, Gamma – ray arrival
• Another acceleration mechanism have to be found…
SEP’s acceleration by interplanetary shock waves
Magnetic reconnection as a main force for solar flare particle acceleration

Solar flare standard model
Particle Acceleration in Flares

• Acceleration by DC electric field in Reconnecting Current Layer

  plus...

• Collapsing trap dynamics
• Stochastic dynamics (waves, shocks)
Scenario of acceleration process

After Somov & Bogachev

- Magnetic field lines move to the X-type neutral point

-The electric field is induced and accelerates particles

\[ E = -\frac{1}{c} \frac{\partial A}{\partial t}, \]

Magnetic reconnection as an injector
Evidences from observations

- Thermal and non-thermal HXR emission from the corona, can be interpreted as reconnecting super-hot turbulent-current layer (SHTCL)

1991-2001

Yohkoh data

*Tsuneta S., Kosugi T.*

2001-2006 SPIRIT/CORONAS-

F I. Zhitnik, C.Kuzin
Scenario of acceleration process

1. Magnetic reconnection as an injector

2. Electron capture and collapse of magnetic trapping region

Bethatron acceleration connected with collapse of magnetic loops with simultaneous Fermi acceleration (stochastic acceleration)
Do we have bethatron acceleration somewhere else?

- Yes, nearby
Radiation belts
Radial diffusion - the main transport process of RB particles

Magnetic diffusion example

Solar wind fluctuations

Fluctuation of geomagnetic field

Induced electric field

Particle’s drift in crossing over ExB fields

Diffusion across L-shells

D - diffusion coefficient as a critical parameter of radiation belts dynamics
SEP acceleration mechanism should explain experimental data:

Acceleration of

- Protons up to $1-10 \text{s}$ 300MeV- $\sim$several GeV
- Electrons up to $\approx 0.5 \text{s}$ 60-100MeV

SM gives
Acceleration of protons and electrons

Protons can be accelerated up to GeV, but electrons only up to several MeV. Dependent on the plasma parameters.

Bogachev, et al
SEP acceleration mechanisms

A: Electric Fields: **Parallel to B Field**

B: Fermi Acceleration

1. Shocks: **First Order Fermi**

2. Stochastic Acceleration: **Second Order Fermi**
• Do we have reconnection somewhere else?
Reconnection is everywhere

In the magnetospheres

At the Sun
Magnetic substorms/storms
reconnection

Particles acceleration
and movement to the Earth
• Shock’s acceleration is everywhere as well!
Shock’s acceleration is everywhere as well!

<table>
<thead>
<tr>
<th>SW</th>
<th>GCR</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>$\sim 1\text{cm}^{-3}$</td>
</tr>
<tr>
<td>B</td>
<td>$\sim 1\text{nT}$</td>
</tr>
<tr>
<td>T ion</td>
<td>$\sim 10\text{ eV}$</td>
</tr>
<tr>
<td>Mach</td>
<td>$\sim 5$</td>
</tr>
<tr>
<td>T</td>
<td>$\sim \text{hours}$</td>
</tr>
</tbody>
</table>
SW termination shock
The anomalous cosmic ray component

The main statements of the Fisk, Kozlovski Ramaty theory

Then...

- Acceleration of ionized neutrals, 'picked-up' by the solar wind from ~4 keV/nucleon to >10 MeV/nucleon at the heliopause (termination shock);
The anomalous cosmic ray acceleration

Krymski (1977), Axford et al. (1977) and Blandford and Ostriker (1978):

FIRST ORDER FERMI
OR COMPRESSIVE SHOCK ACCELERATION
ACR spectra near an outer acceleration region

Expected (from Fermi acceleration)

Modulation

ACR before TS and inside the heliosphere

10 MeV/nucleon
Direct observation of ACR acceleration:

Voyager data
ACR He Spectral Evolution

Where is the ACR source?
- Near the ecliptic?
- Along the flanks?
- In the heliosheath?


V1 crossed shock on 2004/351

Expected source spectrum was not observed at time of shock crossing

Where is the ACR source?
- Near the ecliptic?
- Along the flanks?
- In the heliosheath?
ACR source(s)

Alternative (or complementary) approach:

Ionosphere plasma of “magnetic” planets enriched by O+ can be a source for ACR
Ionosphere as a source of plasma in the Earth’s magnetotail
Magnetic substorms/storms
reconnection

Particles acceleration and outflow in antisolar direction
Double acceleration of ACR: during reconnection process in the magnetospheres of the giant planets plus acceleration at heliospheric TS.
Thank you