Propagation of cosmic rays

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GENERAL PROPERTIES OF COSMIC RAYS

- Composition: protons 90%, α-particles 8%, other 2%
- Spectrum of cosmic rays is almost power law
- The only features is a knee around $10^{15}$ eV and an ankle around $10^{19}$
- Same mechanism of propagation for all the cosmic rays
- Averaged energy density of cosmic rays 1 eV cm$^{-3}$ of the order of the Inter Stellar Radiation Field (ISRF), magnetic field and turbulent motion of the interstellar gas ↓
  CR are one of the main component of interstellar medium
Not only SNs and SNRs are CR sources but even pulsars, compact objects in close binary systems, stellar wind.
Propagation Equation for Cosmic Rays

\[
\frac{\partial \psi(r, p, t)}{\partial t} = q(r, p) + \nabla \cdot (D_{xx} \nabla \psi - \mathbf{V}\psi) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \psi
\]

- convection velocity field that corresponds to galactic wind and it has a cylindrical symmetry, as the geometry of the galaxy. It’s z-component is the only one different from zero and increases linearly with the distance from the galactic plane
- diffusion coefficient is function of rigidity
- diffusion coefficient in the impulse space, quasi-linear MHD: \(D_{pp}(D_{xx}, v_A)\)
- loss term: fragmentation
- loss term: radioactive decay
- primary spectra injection index

\[
dq(p)/dp \propto p^{-\gamma}
\]

implemented in Galprop (Strong & Moskalenko, available on the Web)
Distributed Stochastic Reacceleration

Scattering on magnetic turbulences

Fermi 2-nd order mechanism:
Head-on collisions are more frequent than following - particle gains energy

\[ D_{pp} \sim p^2 V_a^2 / D \]
\[ D \sim vR^{1/3} \text{ - Kolmogorov spectrum} \]

Simon et al. 1986
Seo & Ptuskin 1994

Energy gain
Convection

Galactic wind

Escape length

problem: too broad sec/prim peak

$X_e$

$R^{-0.6}$

wind or turbulent diffusion

resonant diffusion

E

Jones 1979
Nuclear component in CR: What we can learn?

**Propagation parameters:**
- Diffusion coeff., halo size, Alfvén speed, convection velocity...

**Energy markers:**
- Reacceleration, solar modulation

**Stable secondaries:**
- Li, Be, B, Sc, Ti, V

**Radio (t_{1/2}~1 Myr):**
- $^{10}$Be, $^{26}$Al, $^{36}$Cl, $^{54}$Mn

**K-capture:**
- $^{37}$Ar, $^{49}$V, $^{51}$Cr, $^{55}$Fe, $^{57}$Co

**Short t_{1/2} radio:**
- $^{14}$C & heavy Z>30

**Heavy Z>30:**
- Cu, Zn, Ga, Ge, Rb

**Material & acceleration sites, nucleosynthesis (r-vs. s-processes):**

**Local medium:**
- Local Bubble

**Diffuse γ-rays:**
- Galactic, extragalactic: blazars, relic neutralino

**Nucleo-synthesis:**
- supernovae, early universe, Big Bang...

**Dark Matter (p, d, e^+, γ):**

**Solar modulation:**
CR Isotopic Abundances vs Solar System Abundances

Very detailed low-energy data exist!

ACE: 100-200 MeV/nucleon

Wiedenbeck+2001

ACE data
Solar System

Relative Abundance \((28\text{Si}=1000)\)

He Be C N O Ne Mg Si S Ar Ca Ti V Cr Mn Fe Co Ni Zn Cu

decay product
radio

20, 21, 22
53, 54, 55

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Enveloping curves of all the good fits of the experimental B/C data

Dashed line: Best fit

**DR**: diffusion + reacceleration
**DC**: diffusion + convection

In DC model problem with the ACE data at low energy

A. Lionetto, A. Morselli, V. Zdravkovic
New CREAM B/C measurements

New CREAM data seem to favour a model with the diffusion coeff. index ~0.5 (e.g. Iroshnikov-Kraichnan model, Ptuskin et al. 2006), but other models can not be excluded yet.
New PAMELA B/C measurements

The HEAO-3 sharp peak at ~1 GeV/nucleon seem to be confirmed by Pamela

(Blois 08)
Cosmic ray accelerators
Stages of CR propagation:

- Acceleration: SNRs, pulsars, Superbubbles, whatever

- Propagation in the interstellar space

- Propagation in the heliosphere
Particle Acceleration in the SNRs

• Not all SNRs are created equal...
• It is difficult to distinguish between hadronic and leptonic scenarios based on the spectral shape in 0.5-20 TeV region alone
• Observational bias: TeV instruments see mostly hard spectrum sources
• The observed CR spectrum is cumulative over a large number of sources
• *GLAST* observation of Galactic sources and the diffuse emission will be critical!

• ISRF is very intense in the inner Galaxy
• *GLAST* will also probe ISRF
• updated from Moskalenko et al. 2002 ApJ paper
• BESS data are in agreement with modulation model (drift model) predictions for the tilt angle = 5-15 degrees (A<0) while the actual angle was ~30 degrees.
• It may tell that the drift model has to be updated for A<0.
An example of a neutralino annihilations induced contributions to the total antiproton flux with the Diffusion and Convection model background that corresponds to the propagation parameters of the best fit of the B/C data. fd: Clumpiness factors needed to disentangle a neutralino induced component in the antiproton flux.
For different values of the mSUGRA parameters one can found the minimal values of the fd needed to disentangle a neutralino induced component in the antiproton flux with PAMELA. This factor can be computed as a function of the mSUGRA parameters. Fixing the less sensitive parameters $A_0$, $\tan \beta$ and $\text{sign} \mu = +1$, the clumpiness factor becomes a function of $m_0$ and $m_{1/2}$.

The PAMELA preliminary antiproton/proton ratio is consistent with the standard production, hence from the analysis in JCAP09 we can exclude the region shown in the next figure.
PAMELA WIMP Detection Sensitivity

$M_{1/2}$ (GeV)

$M_0$ (GeV)

PAMELA allowed region for a boost factor 10

PAMELA excluded region for a boost factor 10

no electroweak symmetry breaking

tg(β)=55, sign(μ)=+1

updated from arXiv:0502406
PAMELA WIMP Detection Sensitivity

$M_{1/2}$ (GeV)

$M_0$ (GeV)

$\tan(\beta) = 55$, sign($\mu$) = +1

WMAP 3 allowed region (95% C.L)

PAMELA excluded region for a boost factor 10

equi neutralino mass curves

no electroweak symmetry breaking

$m_\chi = 400$ GeV

$m_\chi = 300$ GeV

$m_\chi = 200$ GeV
GLAST sensitivity in five years for a Navarro Frank and White (NFW) halo profile and the LHC limits
\( \chi \) not LSP

WMAP 3 allowed region (95\% C.L.)

PAMELA excluded region for a clumpiness factor 10

PAMELA excluded region for a clumpiness factor 1

GLAST limits

\( \tan(\beta) = 60, \text{sign}(\mu) = +1 \)

no electroweak symmetry breaking
Positron spectra: PAMELA expectation for DC model

$E^2$ positron flux (particle / ($m^2 \cdot sr \cdot s \cdot GeV$))

kinetic energy (GeV)

A.Lionetto, A.Morselli, V.Zdravkovic
Positron ratio: Experimental situation and PAMELA expectation for DC model


Positron ratio: Experimental situation and PAMELA expectation for DC model


model with reaceleration
model with no reaceleration

AMS01 single tracks
AMS01 brems events
HEAT e, HEAT pbar comb.

MASS 91 DC
CAPRICE 98
CAPRICE 94
HEAT 94+95
AESOP 94
TRAMP-Si 93
MASS 89
Mueller and Tang 87
Golden et al. 87
Hartman and Pellerin 76
Buffington et al. 75

kinetic energy (GeV)

posion charge fraction $e^+/(e^- + e^+)$

PAMELA 3y expectations

Daugherty et al. 75
Fanselow et al. 69
Agrinier et al. 69
Positron ratio: Experimental situation and PAMELA expectation for DC model


model with reacceleration
model with no reacceleration
and with Protheroe electron spectrum
nucleon spectrum model


model with reacceleration
model with no reacceleration
and with Protheroe electron spectrum
nucleon spectrum model

Positron ratio: Experimental situation and PAMELA expectation for DC model


model with reacceleration
model with no reacceleration and with Protheroe electron spectrum
model with no reacceleration
flat injection spectrum model

Neutralino annihilation

pulsar


Moskalenko IV, Strong Ptuskin, astro/ph0701517
• The key to understanding the origin of the excess in the ratio is the accurate measurement of positron and electron fluxes separately.

• To confirm the DM signature, we should look into the signal in HE pbars (PAMELA) and gamma-rays (GLAST).

• If this is an astrophysical source of positrons, it should be quite close and we should probably be able to see it with GLAST.
Pulsars, Plerions, & SNRs

- Produce electrons and positrons
- Can accelerate up to TeV energies, at least
- May produce spectral features in CR electron and positron spectra
- Current measurements are not accurate enough!
- GLAST will be able to measure CR electrons up to ~1 TeV
Search for the signature of nearby HE electron sources (SNR, pulsars) in the electron spectrum above ~ TeV

Search for anisotropy in HE electron flux (see e.g. Ptuskin & Ormes, XXIV ICRC, Rome, 1995: nearby sources, streaming of local magnetic fields?)

Precise measurement of electron spectrum above 10 GeV (calibration of IC gamma ray flux model, GALPROP)

Search for Dark Matter Signatures (KKDM) – above ~100 GeV (see e.g. Baltz & Hooper, 2004)
5 years of GLAST LAT observation

Spectral break corresponding to LKP with mass 300 GeV

Spectral break corresponding to LKP with mass 600 GeV
Conclusion:

- Astrophysics of cosmic rays and related topics is a very dynamic field: expect many breakthroughs and discoveries soon!
- The PAMELA data has started to probe interesting regions of the supersymmetric parameter space.

More statistics, the higher energy positrons and antiprotons data and GLAST will expand these regions.