Cosmic Rays Astrophysics: A Quick Survey of The Discipline, Its Scope, and Its Applications

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Way Points

☑ The study of cosmic rays (CR)
  what are they?; where do they come from?; how do we observe them?

☑ The physics of CR
  what basic processes are involved? new data? new insights?

☑ The astrophysics of CR
  their source(s), their acceleration and transport, connection with other disciplines, e.g., x-ray and γ-ray astronomy, cosmology; leaky-box galactic propagation model

☑ An application of CR
  space radiation

☑ A sample (theoretical) project at MSFC
  a superbubble origin of CR
Dr. Svensmark (Danish National Space Center) and co-workers believe cosmic rays affect and impact our climate significantly and they should be considered more carefully in large-scale climate models. [Space Science Reviews 93, 175 (2000); Physical Review Letters 85, 5004 (2000).]

Cosmic rays-and-clouds connection has been made before as were cosmic rays and other geophysical phenomena, e.g., C-14

However, this recent conjecture goes farther!
Motivation?

“Varying cosmic-ray flux may explain cycles of biodiversity”

By Bertram Schwarzschild, Physics Today
October 2007
Motivation?

Gamma-ray picture of our moon illuminated by cosmic rays
Two main sources of ionizing radiation:

- **Galactic Cosmic Rays (GCR)**
  - Protons + almost all other nuclei
  - Low intensity (~ 1 cm\(^{-2}\))
  - High-energy (peaks at 500 MeV/N)
  - Sun-modulated by a factor ~4
  - Isotropic

- **Solar Energetic Particles (SEP)**
  - Mostly protons
  - High intensity (~ 10\(^7\) cm\(^{-2}\))
  - Lower energy (~ 100-200 MeV)
  - Random Directional
Near Earth Exposure

George C. Marshall
Space Flight Center

Distribution of terrestrial exposure of few cSv/yr

In-Space expected levels and limits
Protection from GCRs and SEPs

-Materials vary in their ability to shield against GCR nuclei
-Polymeric based materials tend to be most effective but their structural properties remain poor
-Aluminum, like all metals, is a poor GCR shield

...Is there a ‘Dora’ issue here?
GCR near Earth: Solar Cycle Dependence
GCR near Earth: Modulation by the Sun

Heliospheric magnetic field is altered significantly between quiet Sun (Solar minimum) and active Sun (Solar maximum) conditions.

Simplified models can capture this variation with a single ‘modulation parameter’.
GCR near Earth: Observed Spectra

The ubiquitous Zipf-Pareto (power-law) distributions?
GCR near Earth: Observed Composition

GCR composition is altered from their source composition due to propagation in the interstellar medium (ISM)

Mostly spallation reactions with the ISM’s protons producing secondaries like the light nuclei Li, Be, and B, and sub-Fe group

These tell us much about the time GCRs spend and amount of matter they meet in the galaxy since their synthesis
GCR near Earth: Interactions

Atomic and nuclear reactions of GCR with various media produce a host of secondary products. These reactions and products depend on many factors including GCR intensity, media properties, and atomic and nuclear physics parameters. A good amount of needed basic nuclear physics information is largely based on models. Most of these reactions can still be simulated with reasonable accuracy (except when it comes to radiobiological effects perhaps).
A Very Brief History of Cosmic Rays

1912  Victor Hess discovers “extra-terrestrial radiation”

1930s-1940s  Discovery of protons; secondaries; pions

1948  Discovery of helium and heavier nuclei (Z=28)

1960s  Discovery of “ultra-heavy” (Z>28) nuclei; electrons and positrons (x-ray astrophysics)

1970s  Discovery of isotopes

1980s  Age of cosmic rays; ISM properties

1990s  Discovery of antiprotons; ACRs; GCRs with ultra high energies

2000s  Astrophysical source(s) properties

AMS Experiment on Space Station 2010
**Origin of cosmic rays:**
- Supernovae remnants & ISM matter
- Explosive nucleosynthesis:
  - H, He, and CNO burning cycles
  - Nuclear processes:
    - H, He, and CNO burning cycles
    - E-, r-, and s-processes
    - Nuclei heavier than Ni are unstable/stable ones (e.g., Fe)

**Acceleration of cosmic rays:**
- Differentiation (ionization potential, volatility)
- Supernova shock (energetic, diffusive)
- First-order Fermi acceleration (turbulence)

**Transport of cosmic rays:**
- Diffusive – tied to the galactic magnetic field
- Propagation effects (re-acceleration; spallation reactions; radioactive decay…)

**Modulation of cosmic rays:**
- Cyclic (dynamically coupled to the heliosphere)
- Minor energy loss

- 

Atomic number (Z)

- 

Cassiopeia A

SCO OB2
Particles + Fields

... and some rules!
Computation as Experimentation

The Mathematical World

The Physical World

The Would-Be World
**Theoretical Framework**

Ginzburg-Syrovatskii Equation:

\[
\frac{\partial f}{\partial t} = \frac{\partial}{\partial x_i} \left[ \kappa_{ij} \frac{\partial f}{\partial x_j} \right] - U_i \frac{\partial f}{\partial x_i} + \frac{1}{3} \frac{\partial U_i}{\partial x_i} \frac{\partial f}{\partial \ln(p)} + Q
\]

-This equation is the basis of most theoretical/computational work on cosmic rays transport and acceleration.

-It is a statistical (kinetic) description for isotropic distribution functions.

-It applies to energetic particles whenever their speed is greater than Alfvén speed, if scattering (diffusion) is faster than macroscopic time scales.

-Usually supplemented by HD and MHD descriptions for fluids and plasmas.

*Without a theory the facts are silent.* - F.A. Hayek
Fermi Second-Order Acceleration Mechanism


Collisions between an already energetic particle and a moving, massive cloud will on average result in an increase in the particle’s energy according to:

\[
\frac{\langle \Delta E \rangle}{E} \propto \left(\frac{V}{c}\right)^2 \quad \Rightarrow
\]

\[
\frac{dE}{dt} = rE \quad \Rightarrow
\]

\[
f(E) \propto E^{-\eta}; \quad \eta = 1 + (r\tau)^{-1}
\]

The great tragedy of science is the slaying of an elegant theory by ugly facts. - Thomas Huxley
**Fermi First-Order Acceleration Mechanism**


Energetic particles are accelerated by a passing shock as they scatter -and get isotropized- in the turbulence before and ahead of the shock,

\[
\frac{\langle \Delta E \rangle}{E} \propto \left( \frac{V}{c} \right)^{1} \quad \Rightarrow \quad f(E) \propto E^{-2}
\]

All the richness in the natural world is not a consequence of complex laws, but arises from the repeated applications of simple laws.

- L.P. Kadanoff
GCR Acceleration

Diffusive shock acceleration (DSA) theory:

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

\[ f(p, t) \bigg|_{x=0} \propto \left( \frac{p}{p_0} \right)^{-q} \cdot \int_{t'}^{t} \psi(t', p, p_0) Q(p_0, t - t') dt' \]

\[ \langle t \rangle = \int_{0}^{\infty} t \phi(t) dt ; \quad \frac{\sigma^2(t)}{\langle t \rangle^2} \sim \alpha ; \quad \kappa \propto p^\alpha \]

Only for \( \alpha \approx 0 \) is the accel.-time PDF sharp; \( \alpha \) is typically 1/4 to 1/2 !

DSA: No characteristic acceleration time!
- Electron source is within a kpc
- ‘Standard’ model is unable to account for the electron excess
- Electrons and positrons could be products of dark-matter candidates like the Kaluza-Klein particle (620 GeV)
- Controversial!
Turbulence

Still a problem!
A single particle in a 2-d potential field

\[ \frac{1}{2} \cos(x) \cos(y) + \frac{3}{2} \left( \cos(x) + \cos(y) \right) + \frac{5}{2} \]
Many-Body Problem

All three examples have some degree of nonlinearity…

.....nonlinearity is both challenging and exciting……
**Current Project: Anomalous Transport**

**Brownian Motion in 2D**
Gaussian statistics; central limit theorem; well-behaved PDFs

\[ \langle s^2(t) \rangle \propto t^1 \]

**Continuous Time Random Walk**
Non-Gaussian statistics; Breakdown of the CLM; generalized transport; PDFs with long (algebraic) tails!

\[ \langle s^2(t) \rangle \propto t^\beta ; \beta \neq 1 \]
Anomalous Transport of CR

- **Idealized SuperBubble**
  \(~20\) SNe; \(~100\ pc;\ tenuous\)

- **Collective Acceleration**
  SNs acting independently but each according to DSA theory

- **Non-Equilibrium**
  CR particle in two states:
  accelerated or in transit

- **Transport is Anomalous**
  PDFs with long tails

- **Implications**
  CR spectra?; composition?
Remarks

Cosmic rays; from an astrophysics perspective
  – truly multidisciplinary
  – evolving
  – threads many other disciplines

Cosmic rays; from a physics perspective
  – Basic and applied processes: across decades in energy!
  – new phenomena across old and new regimes
  – new approaches and applications

Cosmic rays; from (for) applications perspectives
  – Particulate-radiation environments
  – Space as well as terrestrial
  – Technology driving

Everywhere I go I find that a poet has been there before me.
  - Sigmund Freud
Where to go for more info. on Cosmic Rays...

- NASA HQ and centers’ websites all have lots of information and leads; for example:
  - http://imagine.gsfc.nasa.gov/docs/science/know_l1/cosmic_rays.html

- University physics, geophysics, astronomy… departments; for example:
  - http://www.srl.caltech.edu/

- National laboratories; for example:

- Other space agencies; for example:
  - http://www.esa.int/esaSC/index.html

- Professional societies for example:
  - http://cosparhq.cnes.fr/
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