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

Von Braun Astronomical Society
Huntsville, Alabama
March 21, 2014

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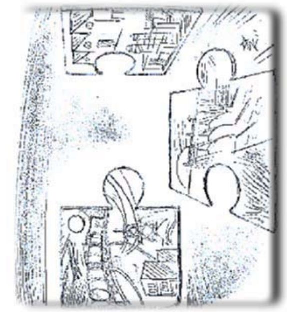
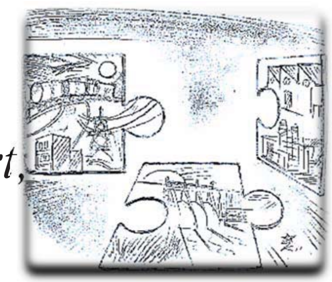
Way Points

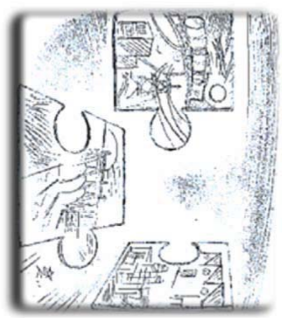
- **The study of cosmic rays (CR)**
  what are they?; where do they come from?; how do we observe them?



- **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



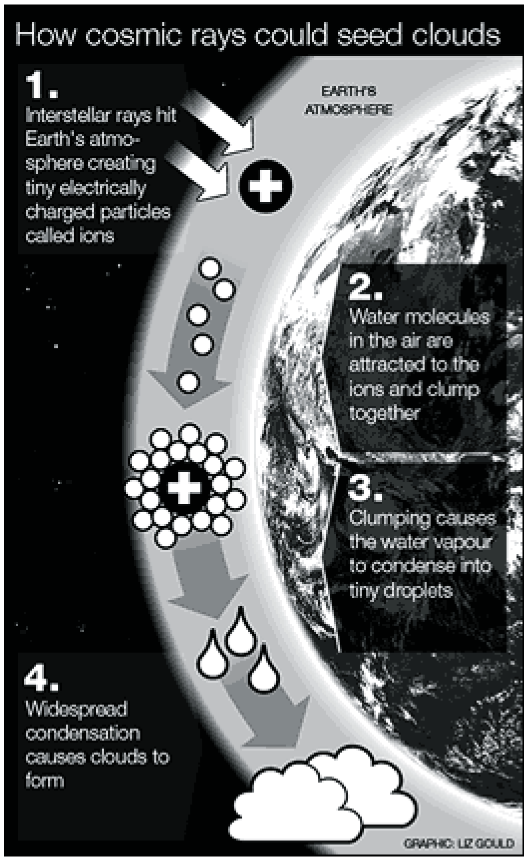
- **An application of CR**
  space radiation

- **A sample (theoretical) project at MSFC**
  a superbubble origin of CR

Motivation?

"Cosmic rays blamed for global warming"

By Richard Gray, Science Correspondent, Sunday Telegraph
(UK)
11/02/2007



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

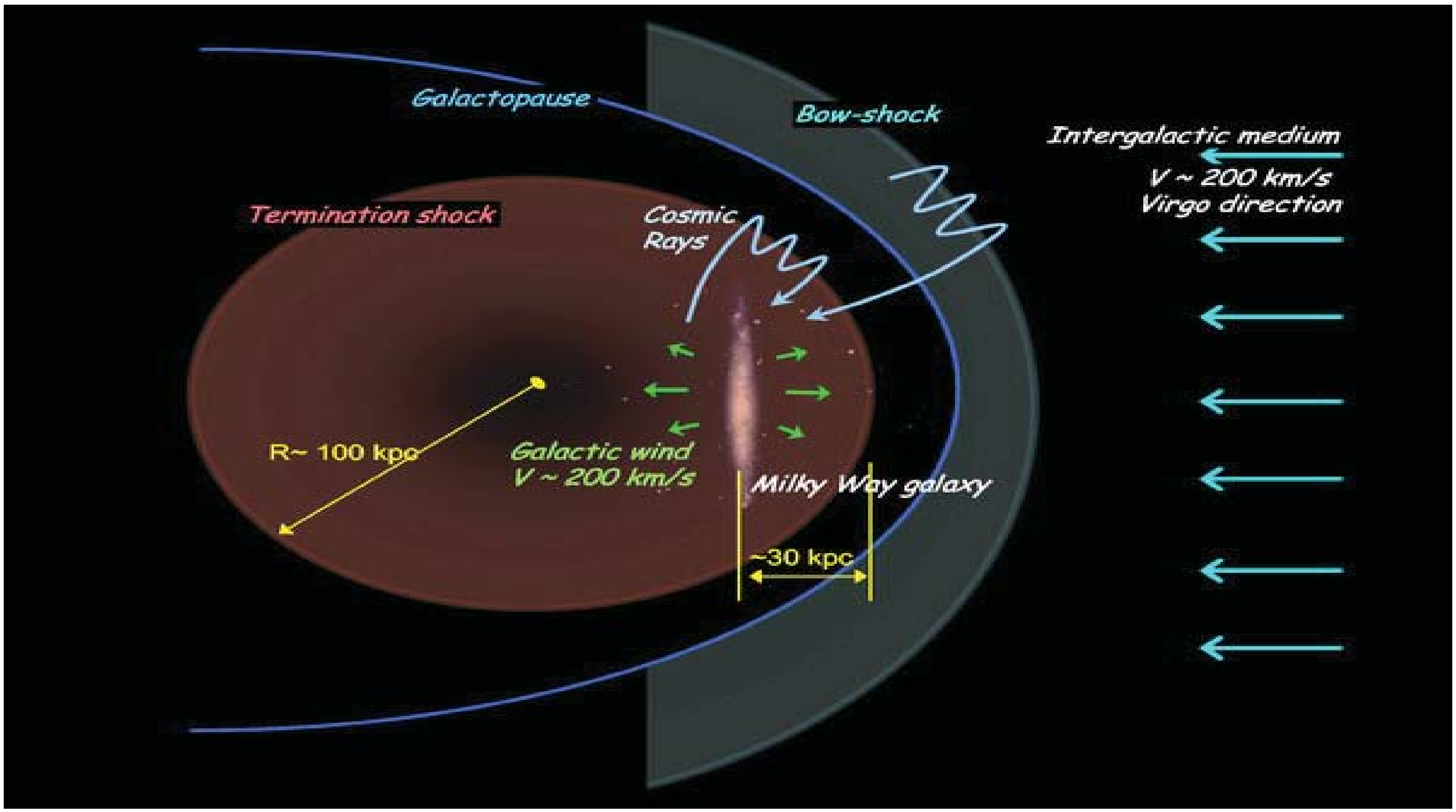
However, this recent conjecture goes farther!

Motivation?

"Varying cosmic-ray flux may explain cycles of biodiversity"

By Bertram Schwarzschild, Physics Today

October 2007

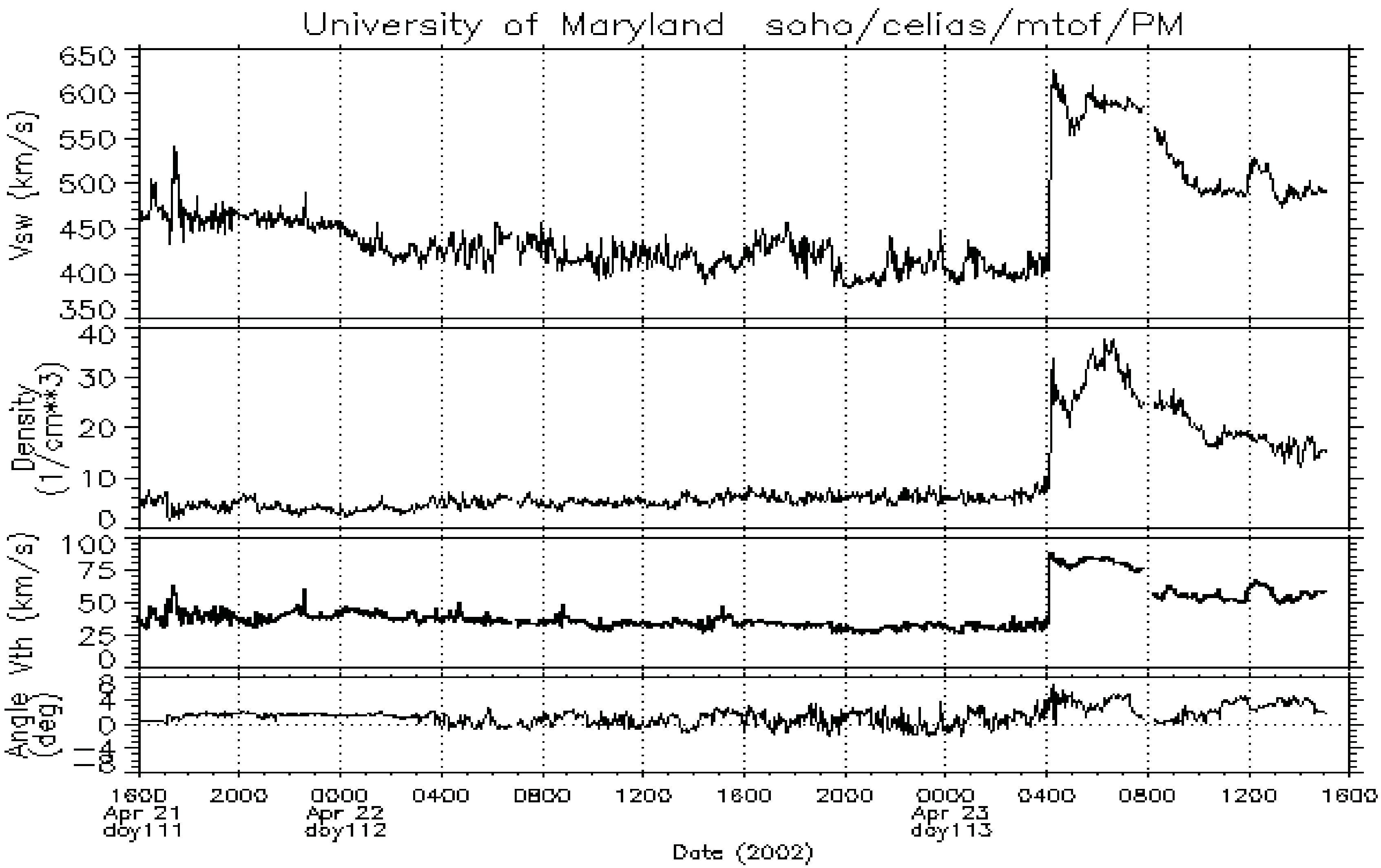


Motivation?

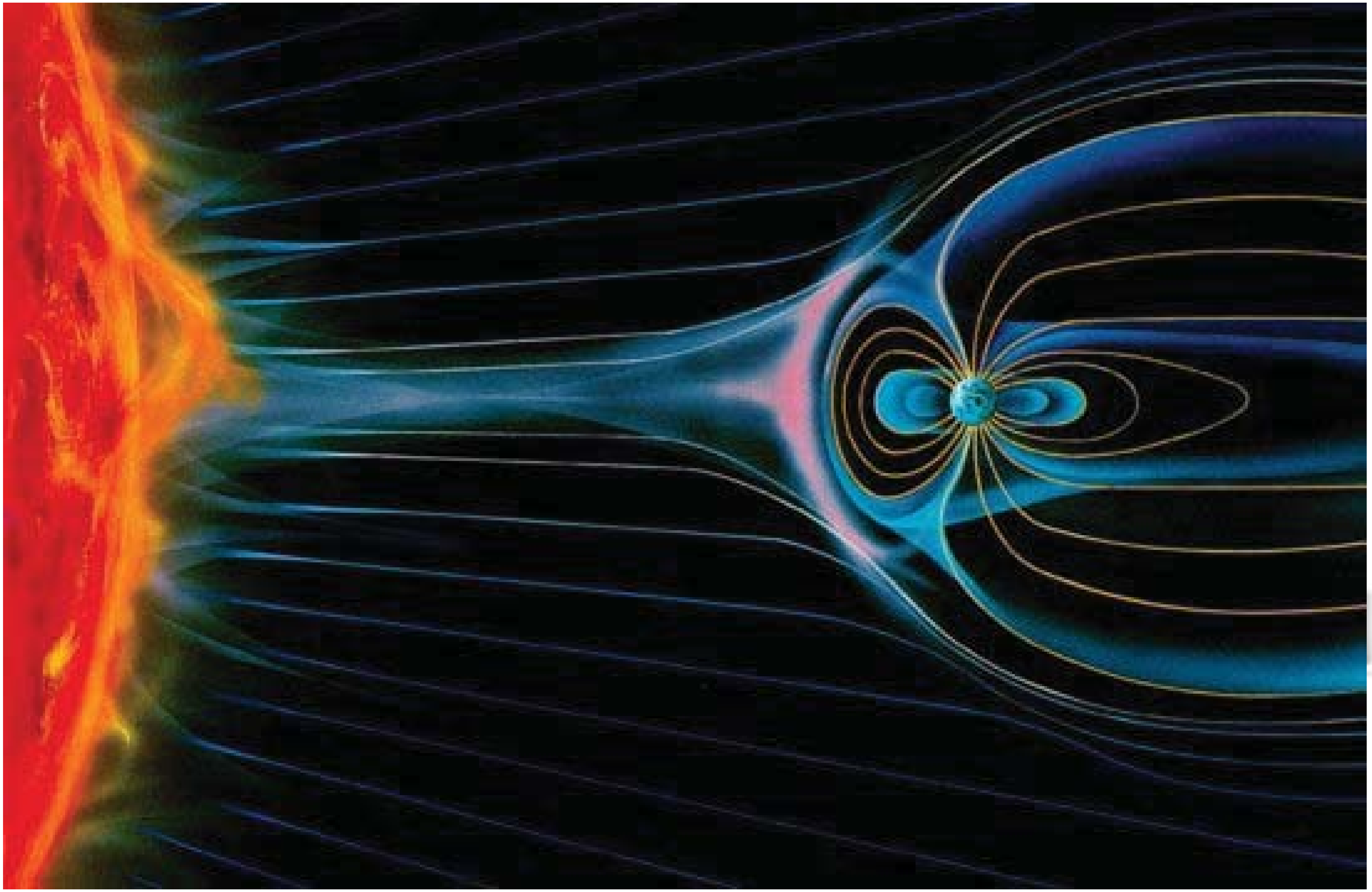
Gamma-ray picture of our moon illuminated by cosmic rays

Near Earth Exposure

Two main sources of ionizing radiation:

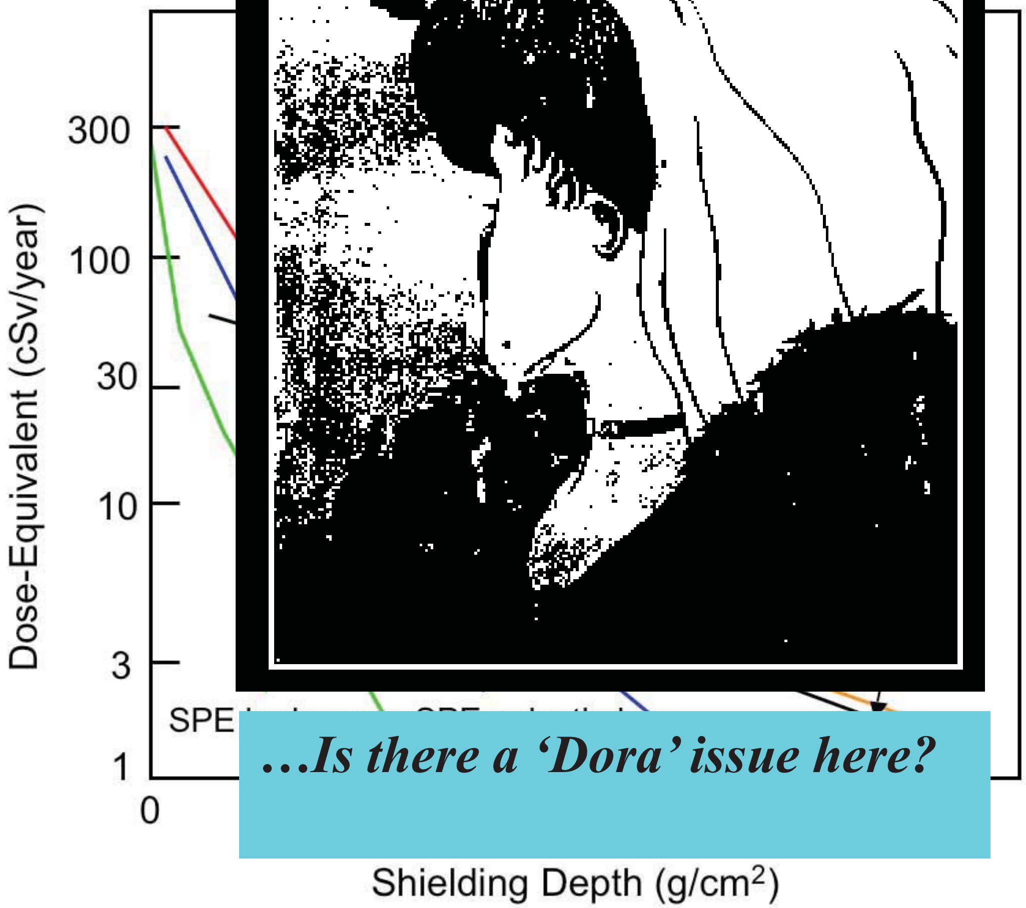


Near Earth Exposure



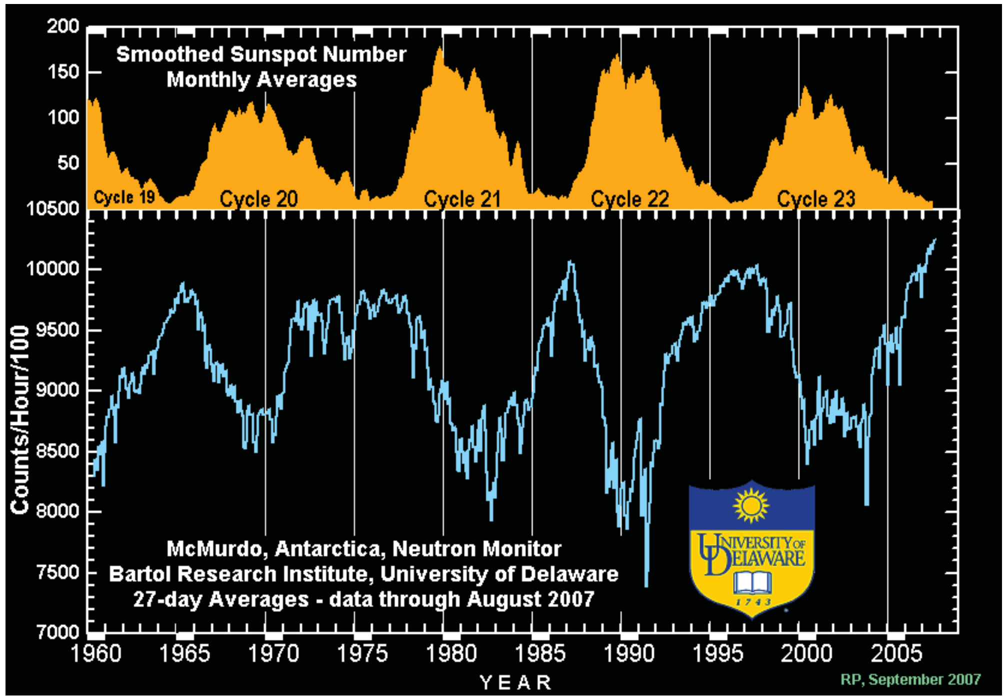
Protection from GCRs and SEPs

-Materials vary ... GCR nuclei
-**Polymeric bas**... **effective** but
their structural ...
-**Aluminum**, lik... **eld**



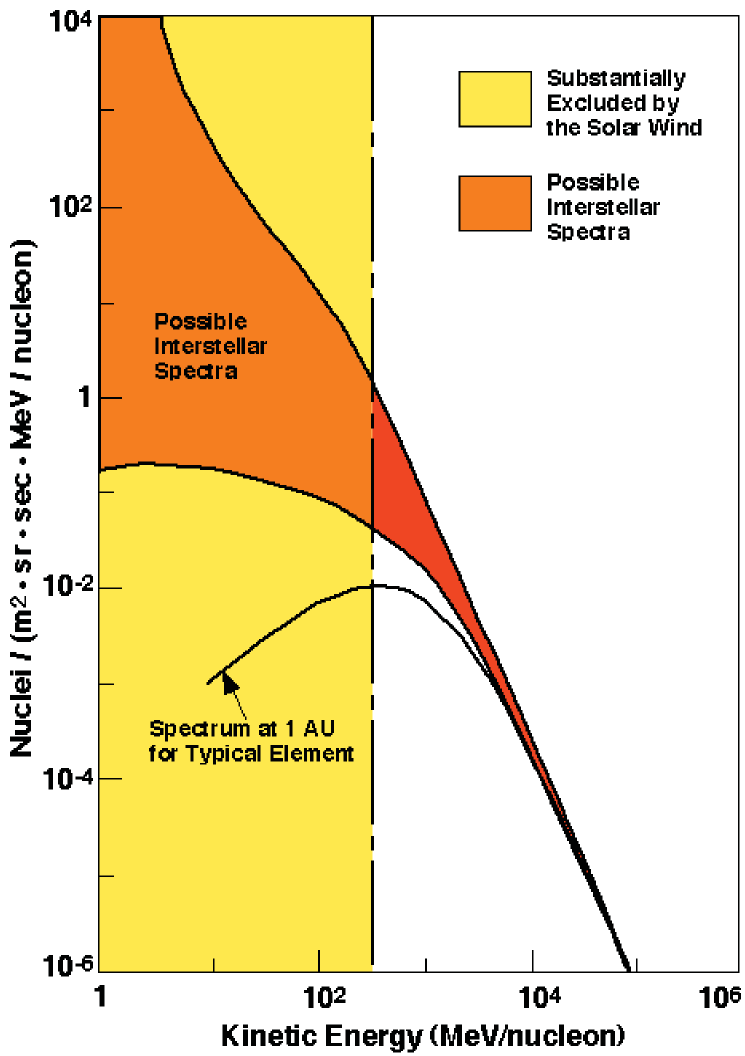
…Is there a 'Dora' issue here?

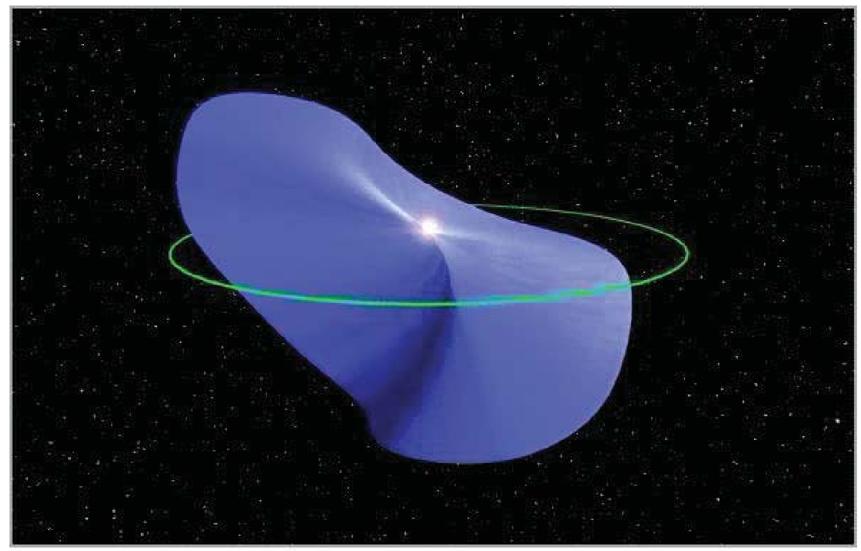
GCR near Earth: Solar Cycle Dependence



GCR near Earth: Modulation by the Sun

George C. Marshall
Space Flight Center

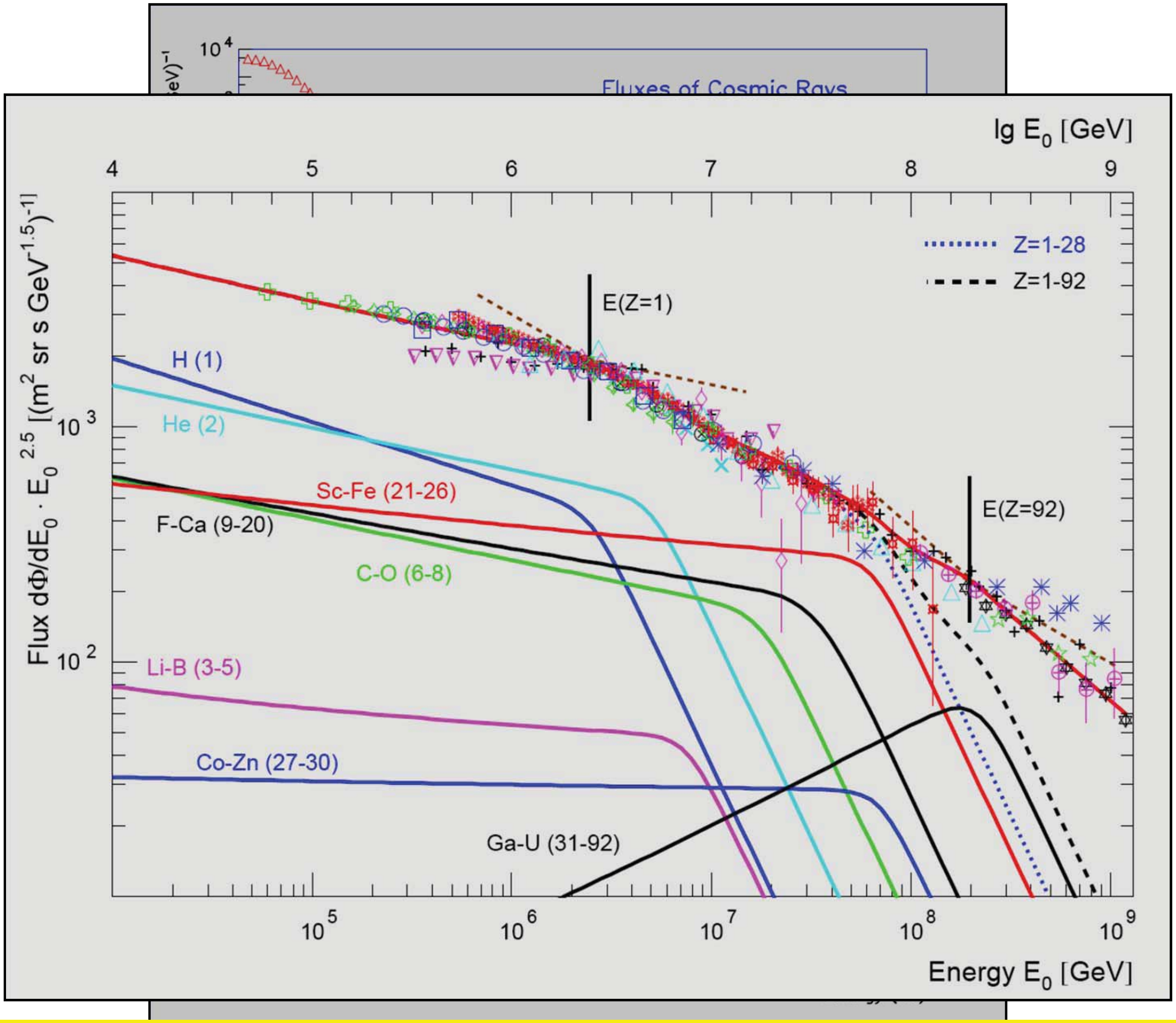




Heliospheric magnetic field is altered significantly between quiet Sun (Solar minimum) and active Sun (Solar maximum) conditions

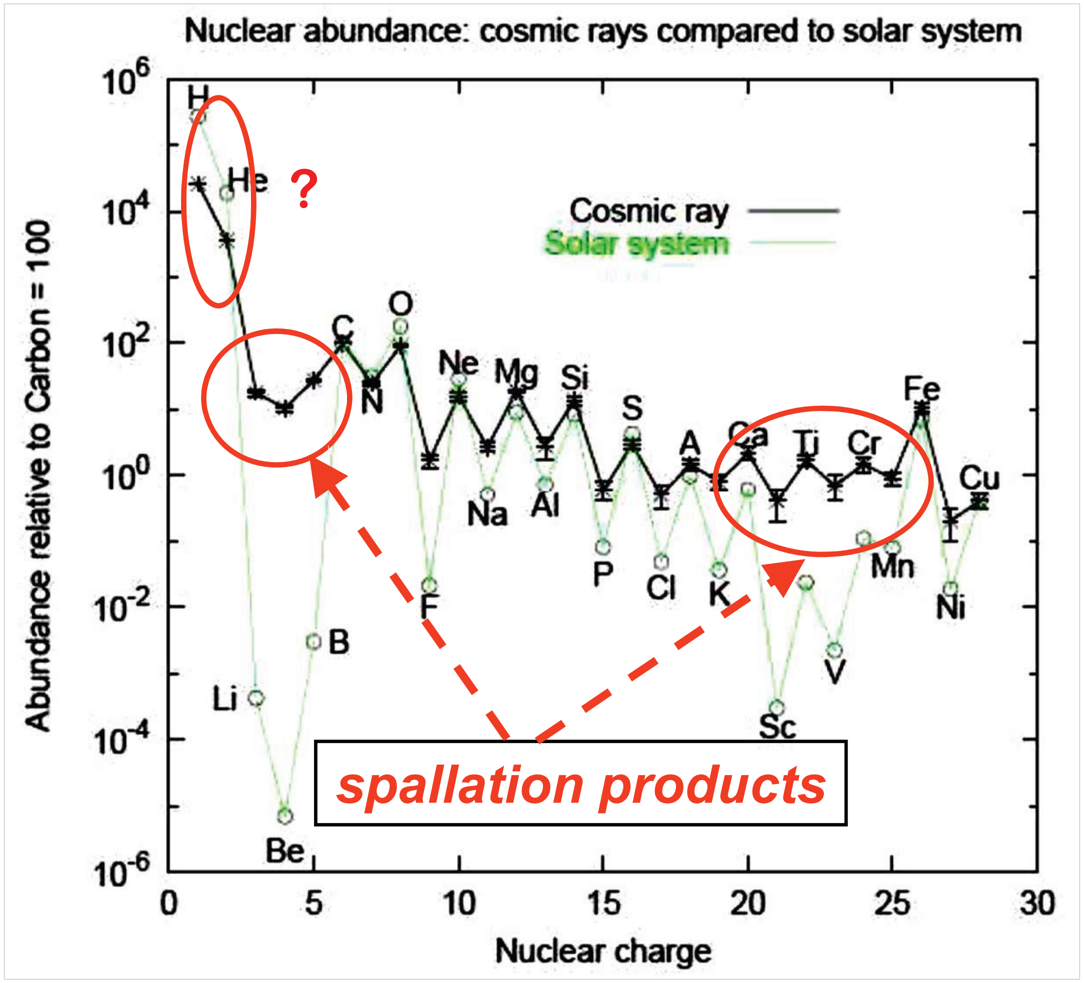
Simplified models can capture this variation with a single 'modulation parameter'

GCR near Earth: Observed Spectra



The ubiquitous Zipf-Pareto (power-law) distributions?

GCR near Earth: Observed Composition

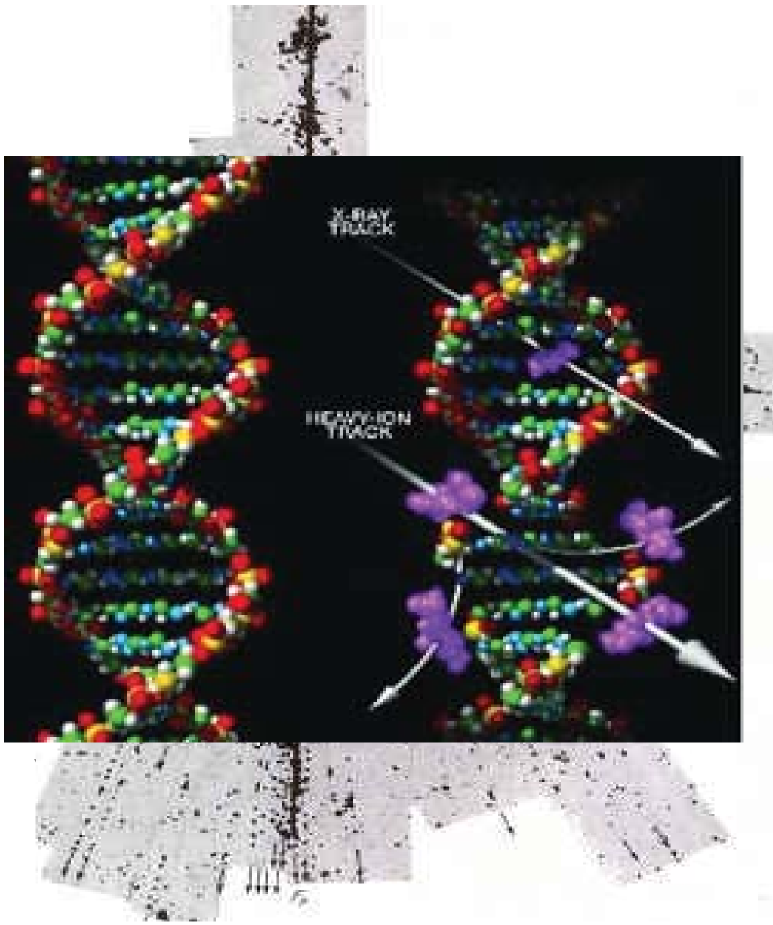


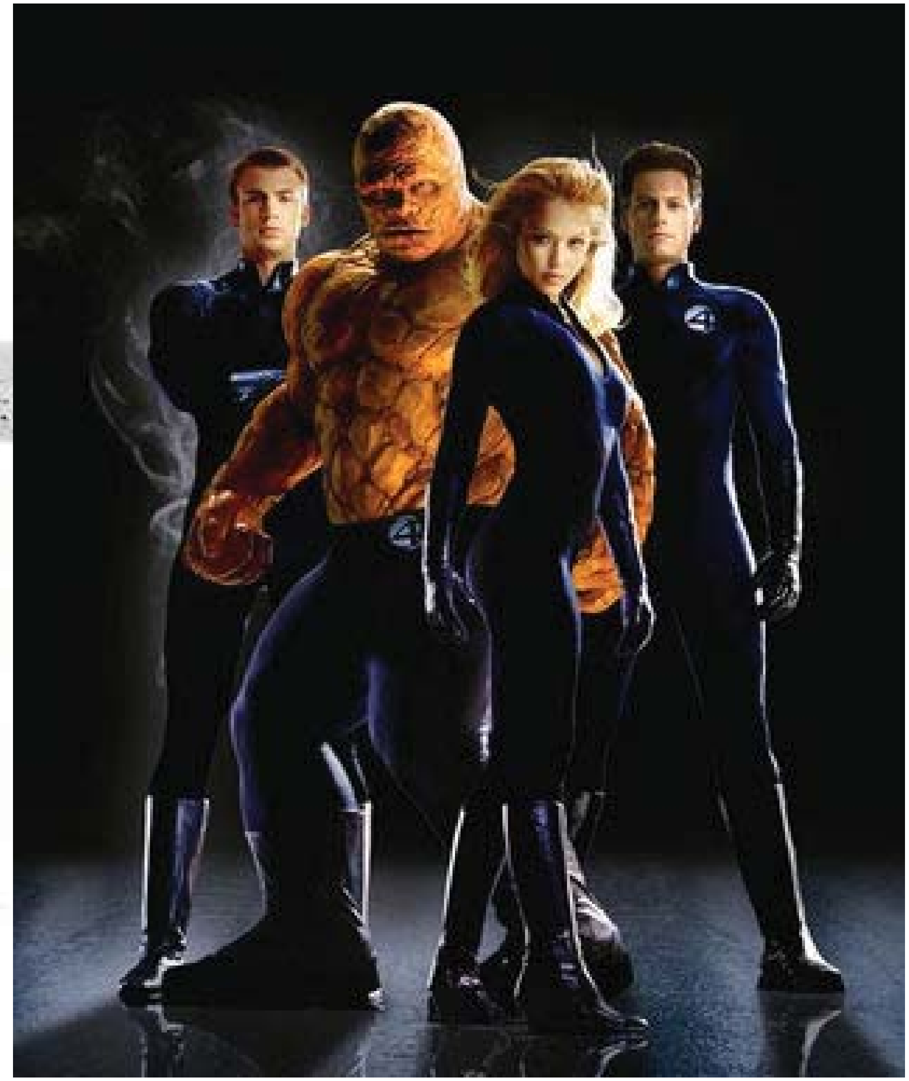
GCR composition is altered from their source composition due to propagation in the interstellar medium (ISM)

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





A *Very* Brief History of Cosmic Rays

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

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

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1980s Age of cosmic rays; ISM properties

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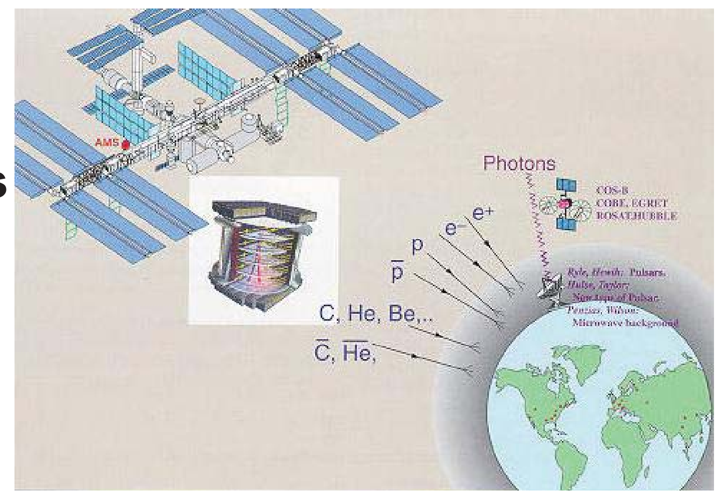
2000s Astrophysical source(s) properties



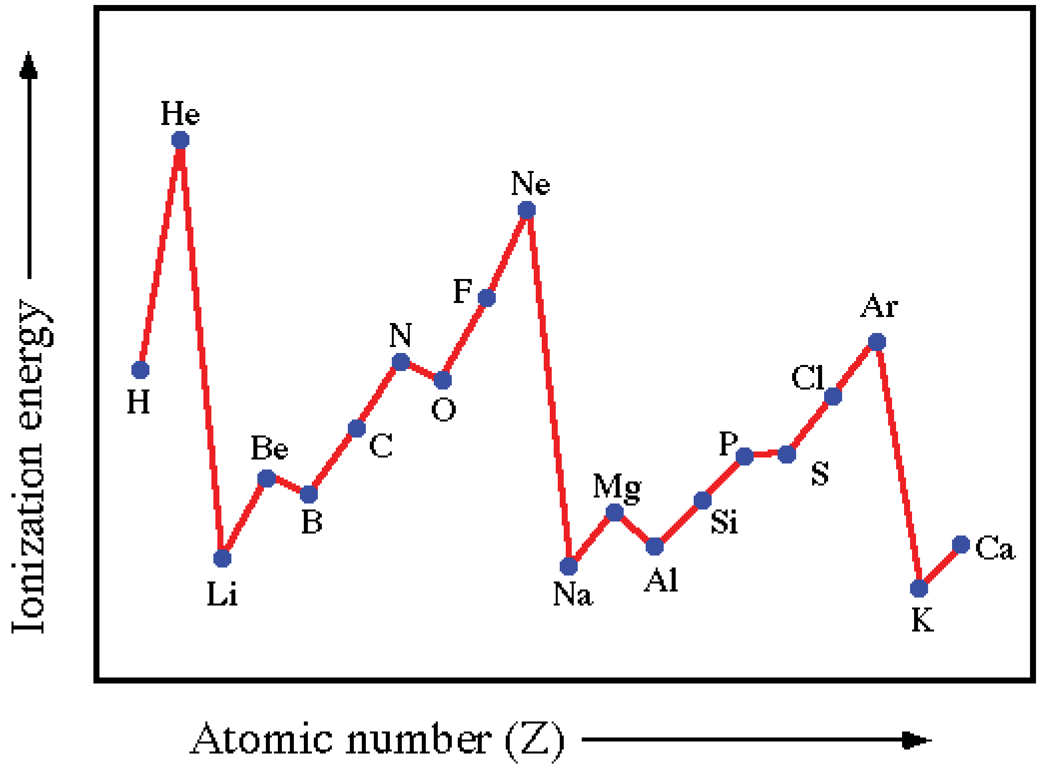
AMS Experiment on Space Station
2010

A Glimpse of Cosmic Rays Astrophysics

George C. Marshall
Space Flight Center

Origin of cosmic rays:

supernovae remnants & ISM matter
explosive nucleosynthesis:
H, He, and CNO burning cycles



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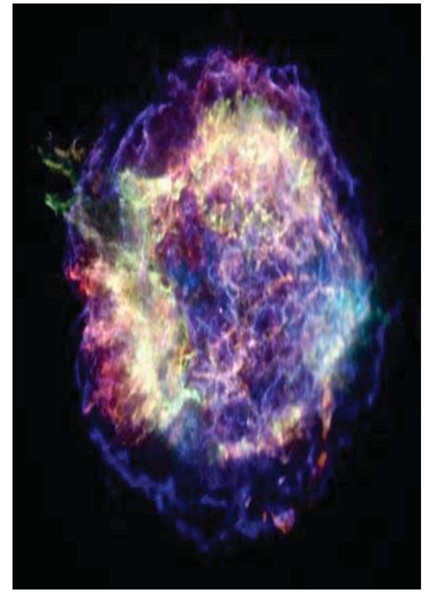
Modulation of cosmic rays:

cyclic (dynamically coupled to the heliosphere);
minor energy loss



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SCO OB2

A Physicist's View of Basic Processes

+

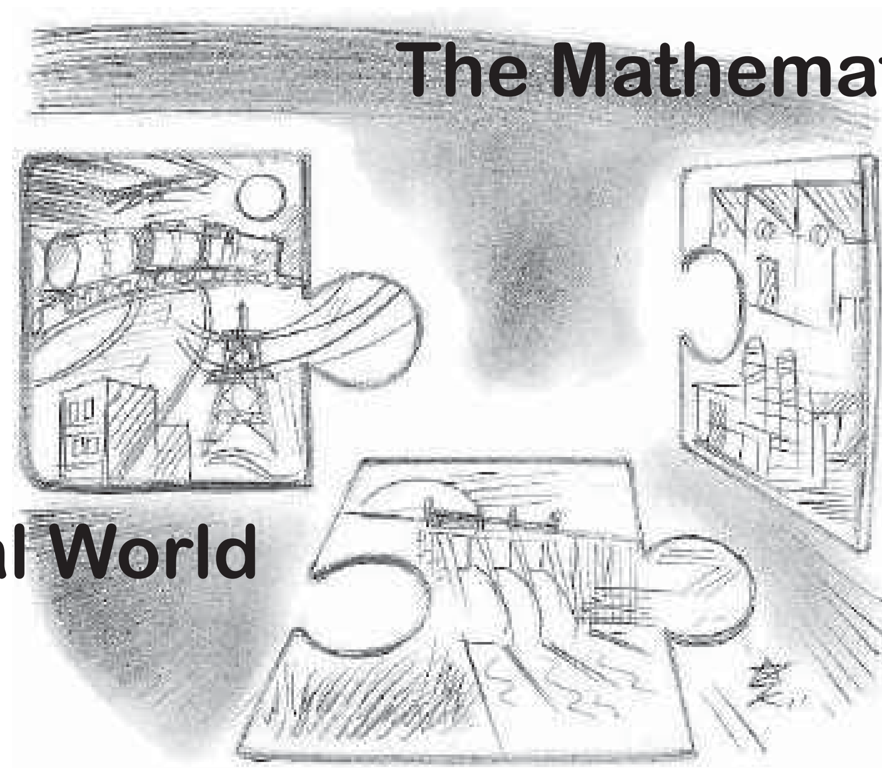
Particles

Fields

… and some rules!

Computation as Experimentation

The Mathematical World



The Physical World

The Would-Be World

Theoretical Framework

Ginzburg-Syrovatskii Equation:

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

-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 $\gg$ Alfvén speed, if scattering (diffusion) is faster than macroscopic timecales

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

Without a theory the facts are silent. *-F.A. Hayek*

GCR Acceleration

Fermi Second-Order Acceleration Mechanism

[E. Fermi, "On the Origin of the Cosmic Radiation," Phys. Rev. **75**, 1169 (1949)]

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:

$$\frac{\langle \Delta E \rangle}{E} \propto \left(\frac{V}{c}\right)^2 \quad \Longrightarrow$$

$$\frac{dE}{dt} = rE \quad \Longrightarrow$$

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

Problem is that the rate of energy increase is too small!

The great tragedy of science is the slaying of an elegant theory by ugly facts. -*Thomas Huxley*

GCR Acceleration

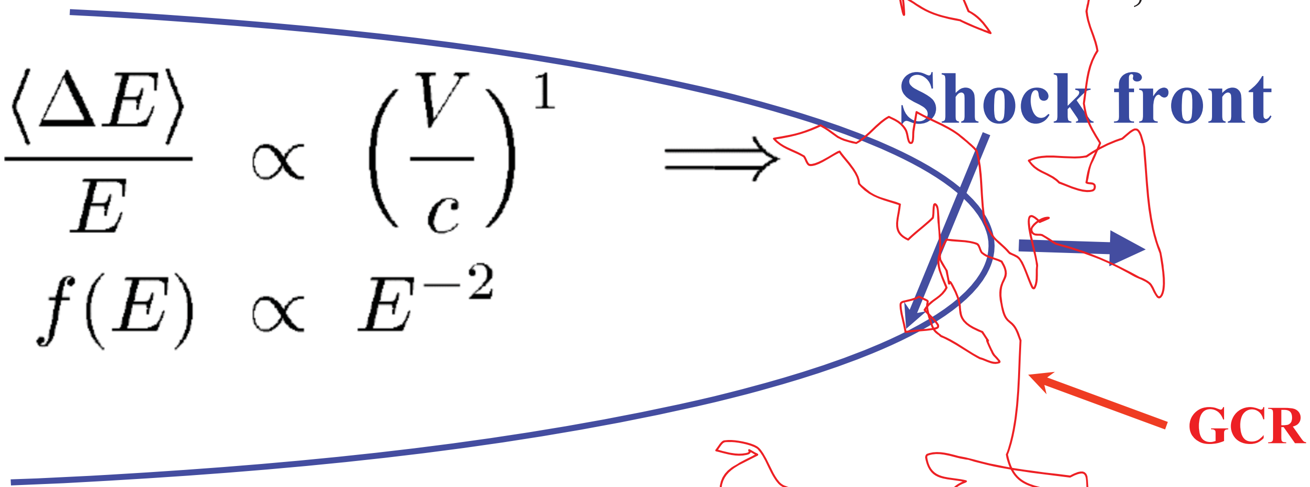
Fermi First-Order Acceleration Mechanism

[E. Fermi, "Galactic Magnetic Fields and the Origin of Cosmic Radiation," Astrophys. J. **119**, 1 (1954)]

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

$$\frac{\langle \Delta E \rangle}{E} \propto \left(\frac{V}{c}\right)^1 \Longrightarrow$$

$$f(E) \propto E^{-2}$$



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:

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

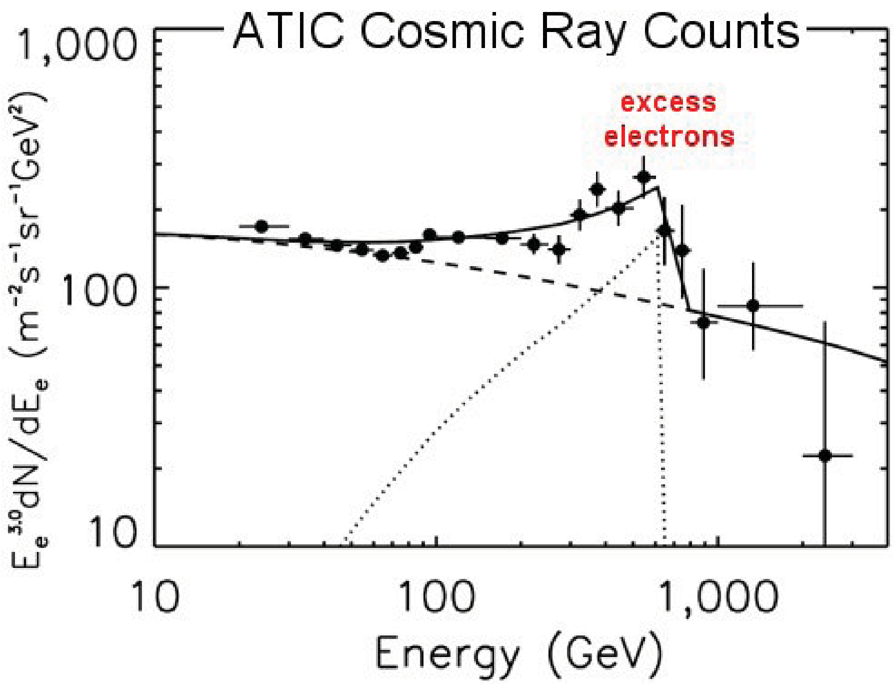
$$f(p,t)\Big|_{x=o} \propto \left(\frac{p}{p_o}\right)^{-q} \cdot \int_o^t \psi(t',p,p_o)Q(p_o,t-t')dt'$$

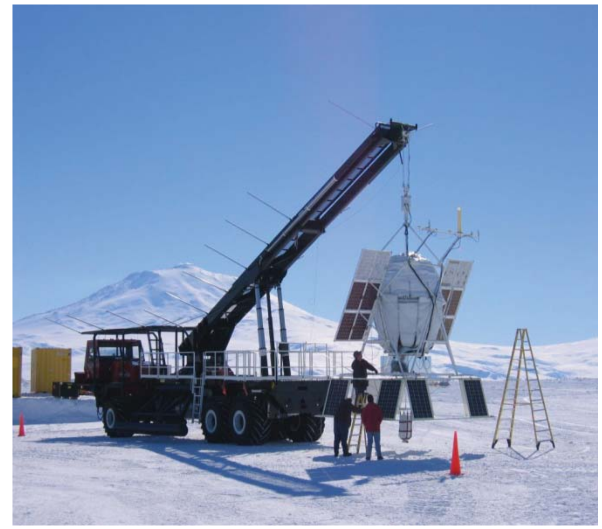
$$\langle t\rangle = \int_o^\infty t\phi(t)dt \;;\; \frac{\sigma^2(t)}{\langle t\rangle^2} \sim \alpha \;;\; \kappa \propto p^\alpha$$

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

DSA: No characteristic acceleration time!

Cosmic Rays & Dark Matter (?)





- 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!

Things Can Get Complicated Quickly

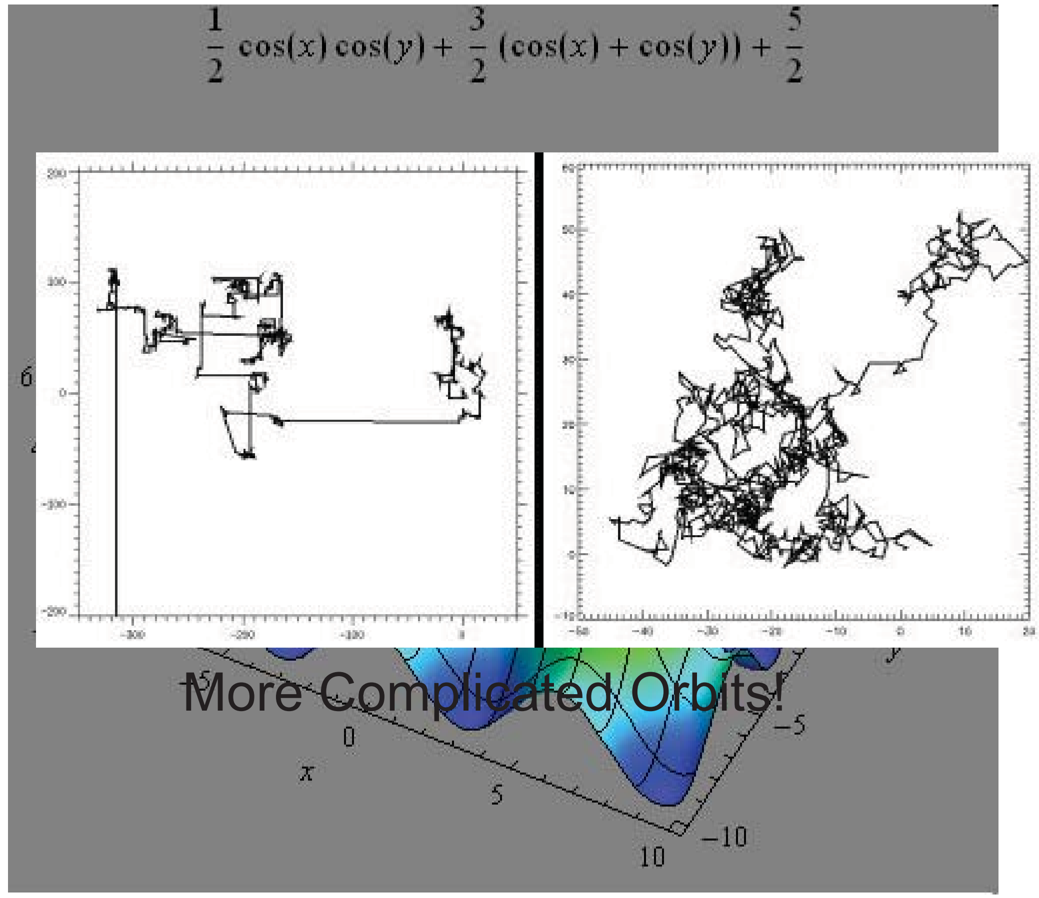
Turbulence

Still a problem!

Things Can Get Complicated Quickly

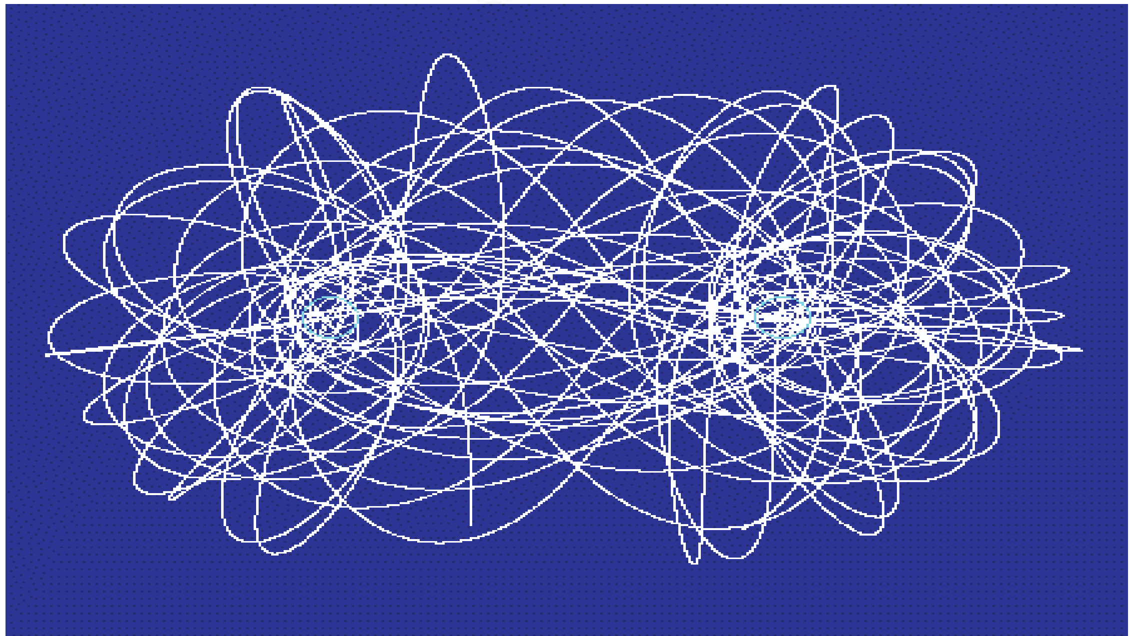
A single particle in a 2-d potential field

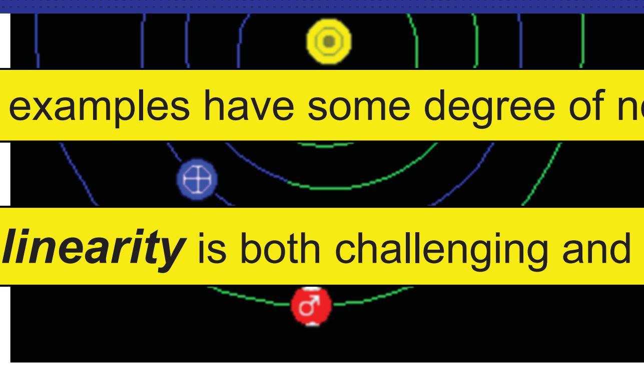
Lévy or Brown?



Things Can Get Complicated Quickly

Many-Body Problem

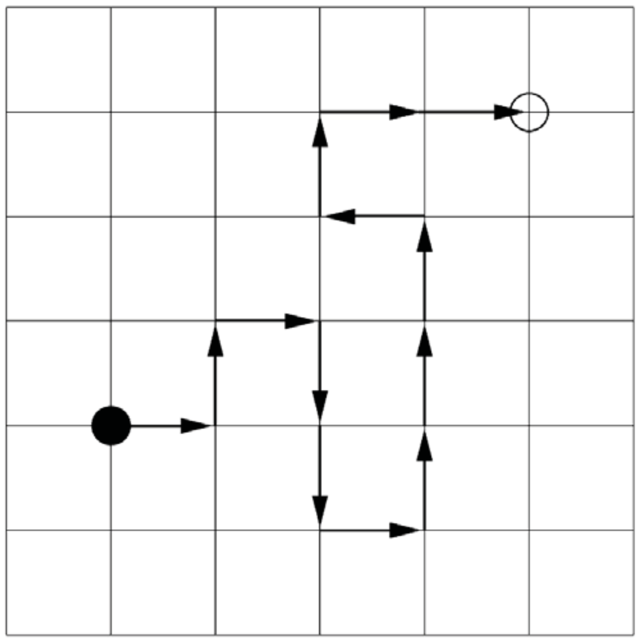




All three examples have some degree of nonlinearity…

…..***nonlinearity*** is both challenging and exciting……

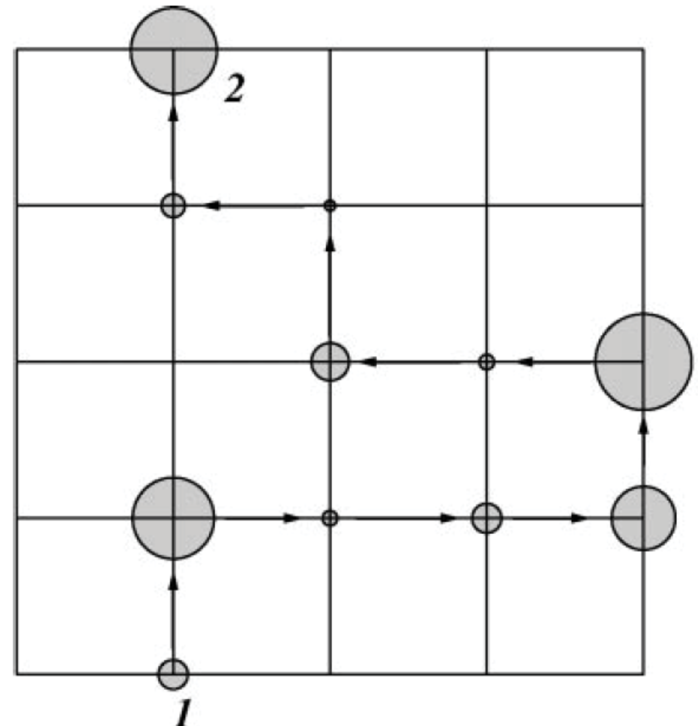
Current Project: Anomalous Transport



Brownian Motion in 2D

Gaussian statistics;
central limit theorem;
well-behaved PDFs

$\langle s^2(t) \rangle \; \alpha \; t^1$



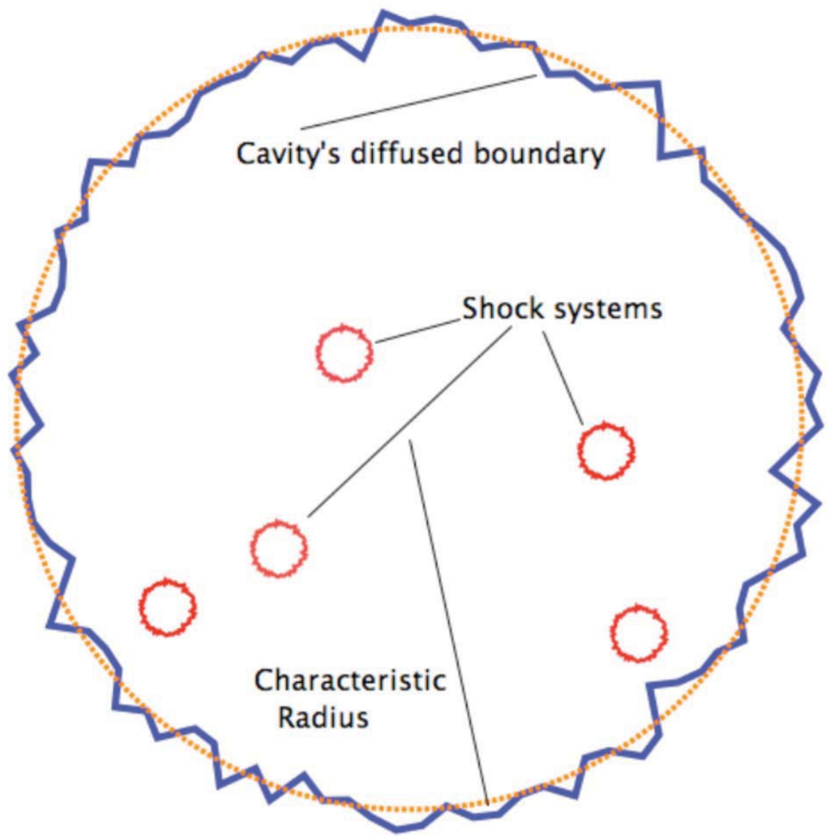
Continuous Time Random Walk

Non-Gaussian statistics;
Breakdown of the CLM;
generalized transport;
PDFs with long (algebraic) tails!

$\langle s^2(t) \rangle \; \alpha \; t^\beta \; ; \; \beta \neq 1$

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:
  - **http://www.ngdc.noaa.gov/stp/SOLAR/COSMIC_RAYS/cosmic.html**
- Other space agencies; for example:
  - **http://www.esa.int/esaSC/index.html**
- Professional societies for example:
  - **http://cosparhq.cnes.fr/**

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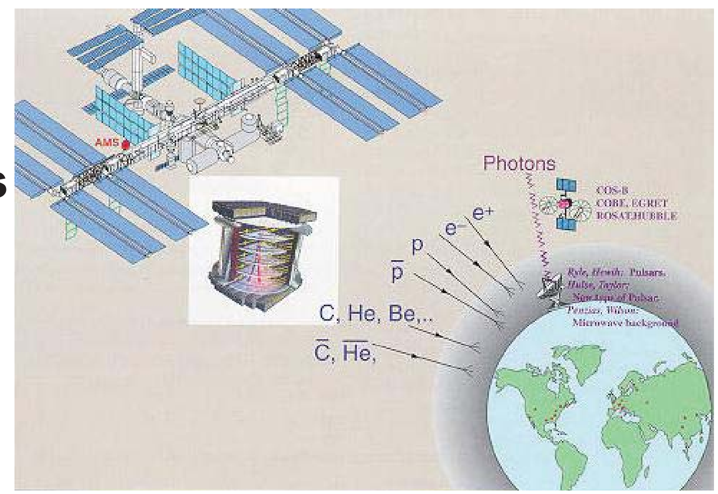

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