

The Radiation Environment on-board the International Space Station

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March 12, 2013

OUTLINE

COSMIC RAYS

THE ISS

SILEYE-3/ALTEINO

SUMMARY AND OUTLOOK

◀ ◻ ▶ ◀ ◻ ▶ ◀ ≡ ▶ ◀ ≡ ▶ ≡

- ▶ 1932 e^+ C.D. Andreson
- ▶ 1949 Fermi Cosmic ray acceleration
- ▶ 1958 "van Alen Belts"
- ▶ 1966 CMB 2.7 K
- ▶ Beginning of 1990
 $2 - 3 \cdot 10^{20} eV$

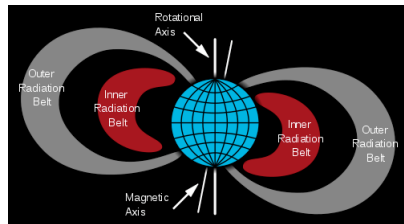


Image from Wikipedia

COMPOSITION OF THE COSMIC RAY SPECTRUM

Particle Composition

- ▶ p , e , and He: 99%
- ▶ 1% Heavy ions
- ▶ Origin? Acceleration?

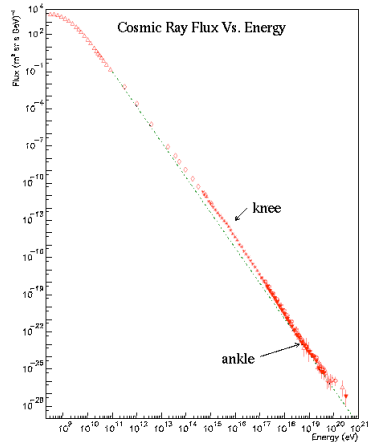


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14. B. P. O'Neil, *Phys. Rev. Lett.* **42**, 200 (1979).
15. J. P. Taylor, *Proc. R. Soc. Lond. A Math. Phys. Eng. Sci.* **376**, 209 (1980).
16. L. W. O'Connell et al., *Phys. Rev. Lett.* **42**, 5302 (1979).
17. J. P. Taylor, *Phys. Rev. Lett.* **45**, 1237 (1980).
18. H. L. Liu et al., *J. Phys. Chem. B*, **104**, 1199 (2000).
19. S. van der Molen et al., *Nature* **426**, 719 (2003).
20. C. C. McMeniscus, *Phys. Rev. Lett.* **79**, 3390 (1997).
21. J. P. Taylor, *Phys. Rev. Lett.* **79**, 3393 (1997).
22. A. G. Scaife et al., *Phys. Rev. B* **61**, 15815 (2000).
23. N. M. Huxley et al., *Phys. Rev. Lett.* **84**, 3618 (2000).
24. J. P. Taylor et al., *Rev. Phys. High. Phys.* **73**, 33 (2001).
25. L. S. Wicks, *Rev. Phys. High. Phys.* **73**, 53 (2001).
26. A. A. Suvorov, J. Pajdova, C. Farnocci, L. Taylor, *Sov. J. Plasma Phys.* **6**, 116 (2000).
27. A. Suvorov et al., *J. Phys. Chem. Atoms Opt. Phys.* **107**, 5053 (2003).
28. A. Suvorov et al., *Phys. Rev. Lett.* **91**, 175801 (2003).
29. A. Suvorov, *Phys. Rev. Lett.* **91**, 245801 (2003).

31. S. S. Kirby, *Phys. Rev. D*, **36**, 3, 666 (1987); *ibid.*, **36**, 3, 667 (1987); *ibid.*, **36**, 3, 668 (1987).
32. R. Mieses et al., *Phys. Rev. D*, **38**, 3, 2350 (1988).
33. C. D. Carney et al., *Phys. Rev. Lett.*, **61**, 10, 1219 (1988).
34. A. K. Takasugi et al., *J. Phys. Soc. Jpn.*, **58**, 10, 1956 (1989).
35. H. Takahashi, T. M. Rice, *Ann. Phys.*, **161**, 1, 121 (1979).
36. A. Benich, *Phys. Rev. Lett.*, **62**, 43 (1989).
37. J. R. Tesse, *Geometry and Physics* (Clarendon Press, Oxford, 1989).
38. S. S. Adler et al., *PRISM Collaboration*, *Phys. Rev. Lett.*, **69**, 23 (1982).
39. T. Schaefer, *Phys. Rev. A*, **37**, 10, 3005 (1988).
40. C. de Dominicis, *Phys. Rev. D*, **18**, 10, 3533 (1978).
41. D. T. Sivers, *Ann. Phys.*, **157**, 1, 1 (1979).
42. P. K. Kishor, D. T. Siva, & A. G. Srinivasan, *Phys. Rev. Lett.*, **59**, 23 (1987).
43. A. V. Andreev, S. A. Buzdun, B. Svirid, *Phys. Rev. Lett.*, **58**, 24, 2404 (1987).
44. A. Benich et al., *Phys. Rev. D*, **37**, 10, 3412 (1988).

Acknowledgments We are grateful to the following organizations for help: H. N. Bailey, B. Wolfe, and C. Kuehnert of the Manly Park Institute for the Chemical Physics of Solids in Graham; the High-temperature neutron measurements at GRS/ISIS; the High-temperature X-ray measurements at I. Lindqvist, G. K. Royster, C. A. Pardo, and J. Janssen; the research was supported by the UK Engineering and Physical Sciences Research Council, and, gratefully, acknowledges funding from the Gates Foundation (Energy and Health) in Research Personnel Recruitment, and EPSRC, which also funded the author's Royal Society visit in their honor.

Supplementary Materials
Supplementary materials are available for this article. For more information on this feature please see the article web link at <http://dx.doi.org/10.1002/anie.201200443>.
Materials and Methods
Supplementary Text
References
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jects and is then transferred to kinetic and thermal energies of shocked molecular gas and subatomic particles. The shocked gas and a large number of subatomic particles are ionized and produce the thermal and nonthermal emission of a supersonic source (SNR). The evolution of a supersonic source (SNR) is the evolution of diffusive shock acceleration (DSA) and magnetic reconnection. The characteristic particle size is $\sim 10^{16}$ (17) Å, generally produced by the subatomic particles in the shock. The acceleration of subatomic particles is related to relativistic shocks (RSNs) and the shock rates of acceleration of the galaxy cluster are 70% to 76% of the supersonic kinetic energy transfer and are transferred to relativistic particles. Therefore, the presence of relativistic particles in SNRs has been mostly inferred from indirect evidence (12–15).

A direct signature of high-energy proton production is provided by gamma rays generated in the decay of neutral pions in the proton-proton collision. Generally nuclear (and) solid-state cosmic-ray detectors, which usually quickly decay into two gamma rays (6-8) (schematically written as $p + p \rightarrow \pi^0 + \pi^0 + \text{other products}$, followed by $\pi^0 \rightarrow 2\gamma$) can thus have an energy of $\sim \sqrt{2} \times 67.5 \text{ MeV}$ in the rest frame of the neutral pion (where π^0 is the rest mass of the neutral pion and c is the speed of light). The gamma-ray emission spectrum, $R(E_\gamma)$, is thus expected above 67.5 MeV to be proportional to the proton flux, Φ_p , in the beam. In the beam π^0 decays are expected to be in the beam π^0 spectrum, which is strongly below $\sim 200 \text{ MeV}$ and approximately follows the energy distribution of proton production, $\Phi_p(E_p)$, where E_p is the proton energy. Therefore, $R(E_\gamma)$ is also $\propto \Phi_p(E_p)$.

active spectral lines (often referred to as the "pin-daisy bump") uniquely identifies β -decaying nuclei and thereby high-energy protons after a measurement of the source spectrum of cosmic rays.

SNRs permeate our high-density clouds, π -decay gamma-ray emission is expected to be enhanced because of more frequent pp interactions relative to the interstellar medium (10). Indeed, SNR

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Detection of the Characteristic Pion-Decay Signature in Supernova Remnants

[illegible]

Chronic rays are a particle beam mostly composed of sub-relativistic speeds. Despite the fact, astrophysical neutrinos (SNB) are the sources of galactic cosmic rays, unambiguous identification of neutrinos in these objects is still lacking. When accelerated protons or nuclei material, they produce neutral pions, which in turn decay into gamma rays. This offers a direct method to detect the acceleration sites of protons. The identification of pion-decay gamma rays is because high-energy neutrinos also produce gamma rays via bremsstrahlung and pair annihilation. We simulated the detection characteristics of pion-decay feature in the gamma-ray spectra and WISE with the Fermi Large Area Telescope. This detection provides distinctive information on acceleration in SNB.

A supernova explosion drives its progenitor material supernovically into interstellar space, forming a collisionless shock wave ahead of the stellar ejecta of kinetic energy released by $\sim 10^{51}$ eV, is initially carried

elques and is then transferred to kinetic and thermal energies of sheared macromolecular gas and solvated particles. The sheared gas and solvated particles produce the thermal and mechanical energies of a supercritical fluid (SNF). The mechanisms of efficient shock deceleration (DSC) can explain the production of solvating particles in SNF (9). DSC generally predicts that the adiabatic fraction of the shock wave is 0.25 for subcritical fluids and 0.33 for supercritical fluids.

Abstract: In this paper, we have shown that the shock-induced turbulent plasma, indeed, SNF, are the main sites of nucleation of the galactic cosmic rays, i.e., they are 70 to 90% of the supernova kinetic energy mass and are proportional to relativistic particle mass. However, the presence of solvated particles in SNF has been mostly inferred from indirect observations (12-15).

A direct signature of high-energy proton production is provided by gamma rays generated in the decay of a neutral pion, i.e. π^0 -proton-pion collisions, generally nuclear-nuclear collisions create mesons, which usually quickly decay into neutral gamma rays ($m\pi$) (chemically written as $\pi^0 \rightarrow \gamma + \gamma$ + other products, followed by $\pi^0 \rightarrow 2\gamma$) each having an energy of $\sim (1/2 \times 675 \text{ MeV})$ in the rest frame of the neutral pion (where m is the rest mass of the neutral pion and c is the speed of light). The gamma-ray emission spectrum, $R(E_\gamma)$, is thus symmetric about 675 MeV and was taken as the reference spectrum. The E_γ distribution was in the range $E_\gamma \approx 600$ MeV, representative of the range below ~ 2100 MeV and approximately covers the energy distribution of prompt pions at atmospheric altitudes from ~ 500 GeV. This is the

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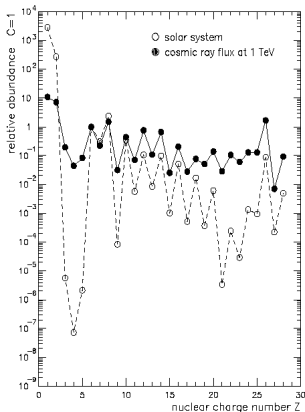


Image taken from Simpson 1983

The Composition of Heavy Nuclei

- ▶ $\frac{dE}{dx} \propto z^2$
- ▶ $\text{Fe} \approx 0.02\%$
 $\rightarrow 20\text{-}50\% D_{eq}$

(D_{eq} = Equivalent dose)

THE HEALTH RISK

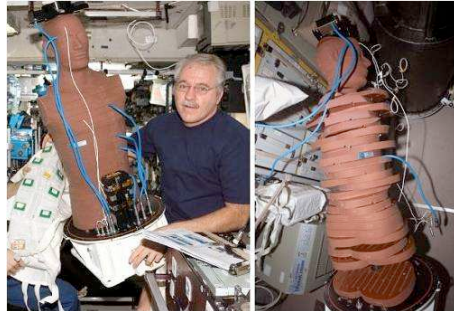
The ability to *a priori* accurately predict health risks is paramount for the future of space exploration.

THE INTERNATIONAL SPACE STATION



The Matroshka Dosimeter

- ▶ SilEye-3/Alteino
- ▶ AMS
- ▶ Passive dosimetry
TEPC, CR-39 etc.



Detector characteristics

- ▶ 8 Silicon Planes
- ▶ 32 Strips/Plane
- ▶ Particle Abundance
- ▶ Shielding effect
- ▶ Dose measurement
- ▶ Fragmentation analysis



Image NASA

RELATIVE ABUNDANCE

Relative Abundance in the Russian Pirs module

EQUIVALENT ALUMINIUM

Modulated ratio of particle abundance:

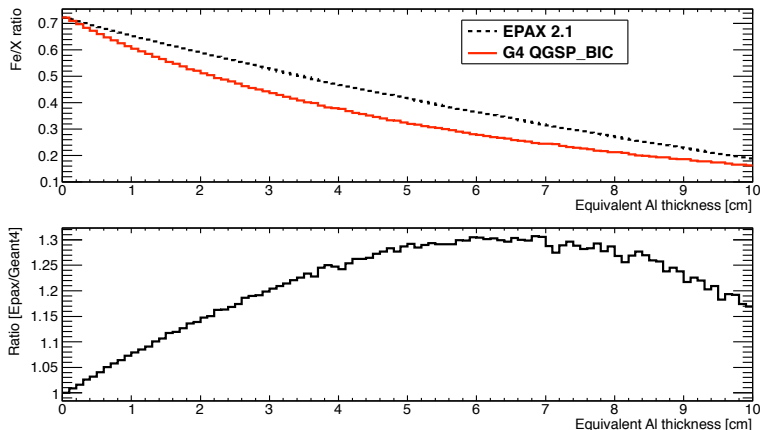
$$P(Fe \rightarrow X) = \frac{\sigma_X N_A}{M_{Al}} \cdot \rho_{Al} \Delta x \quad (1)$$

$$Fe/X = \frac{N_{Fe0}(1 - P(Fe \rightarrow All))}{(N_{X0} + N_{Fe0}P(Fe \rightarrow X))} \quad (2)$$

N_{Fe0} and N_{X0} are number density outside the ISS.

EQUIVALENT ALUMINIUM

Calculating Hull Thickness by Epax 2.1 and Geant4 QGSP_BIC



DOSE AND EQUIVALENT DOSE RATES

Effects of data analysis cuts

Data Cuts

- ▶ Angular
- ▶ Multiplicity
- ▶ Energy

DOSE AND EQUIVALENT DOSE RATES

Conversion from LET_{Si} to LET_{H_2O} has traditionally been done by constant factor.

We use

$$\text{Log}(LET_{H_2O}) = -0.2902 + (1.025 \cdot \text{Log}(LET_{Si})) \quad (3)$$

E.R Benton et. al, Radiation Measurements, 45, 2010, 957-959

DOSE AND EQUIVALENT DOSE RATES

Data

- ▶ SilEye-3/Alteino
- ▶ ALTEA
- ▶ Dostel (MIR)
- ▶ CR-39 (JAXA)

DOSE AND EQUIVALENT DOSE RATES

Multiplicity distribution of
events are well confined
however the contribution to D_r
and D_{eq} aren't as well confined.

SUMMARY

The results from SilEye-3/Alteino to date

- ▶ Clear increase in flux of odd charged particles
- ▶ Shielding efficiency of Polyethylene
- ▶ Particle flux non-isotropic
- ▶ Dose and Dose rates are consistent and isotropic

OUTLOOK

For SilEye-3/Alteino

- ▶ Analysis of high multiplicity events
- ▶ δ_e production in data vs Monte Carlo (Geant4)
- ▶ Continuing mapping the radiation environment

General issues for the assessment of radiation risks

- ▶ Several different Monte Carlo codes
- ▶ Multiple physics list
- ▶ Geometry description

OUTLOOK

The risks in long duration and/or deep space missions due to radiation needs to be dealt with in order to continue with such explorations.

Thank You for your Attention!



SRS
Organising Committee

Back Up

ALTEINO DETECTOR DESCRIPTION

SilEye-3/Alteino

- ▶ 8 planes, $8 \times 8 \text{ cm}^2$, $380 \mu\text{m}$
- ▶ $Gf \approx 24 \text{ cm}^2 \text{ sr}$
- ▶ Readout electronics based on Pamela
- ▶ 16 bit ADC
- ▶ Calibration $3.3 \text{ keV}/\text{ADC}_{ch}$
- ▶ Max $dE \approx 174 \text{ MeV}$



Image from <http://wizard.roma2.infn.it/sileye/index.htm>

ALTEINO DATA CUTS

Angular normalisation

- ▶ $\cos(\theta_{inc})$

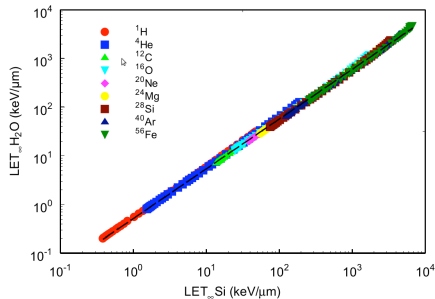
Multiplicity

- ▶ LET: $MSA < 200$ (256)
- ▶ ST: $MSA < 32$ (256)

Kinetic Energy

$$\left| \frac{(E_1 + E_2) - (E_7 + E_8)}{(E_1 + E_2) + (E_7 + E_8)} \right| < 20\% \quad (4)$$

LET CONVERSION, BENTON ET. AL



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