Energetic Particles, Radiation Effects, and Manned Spaceflight

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Overview

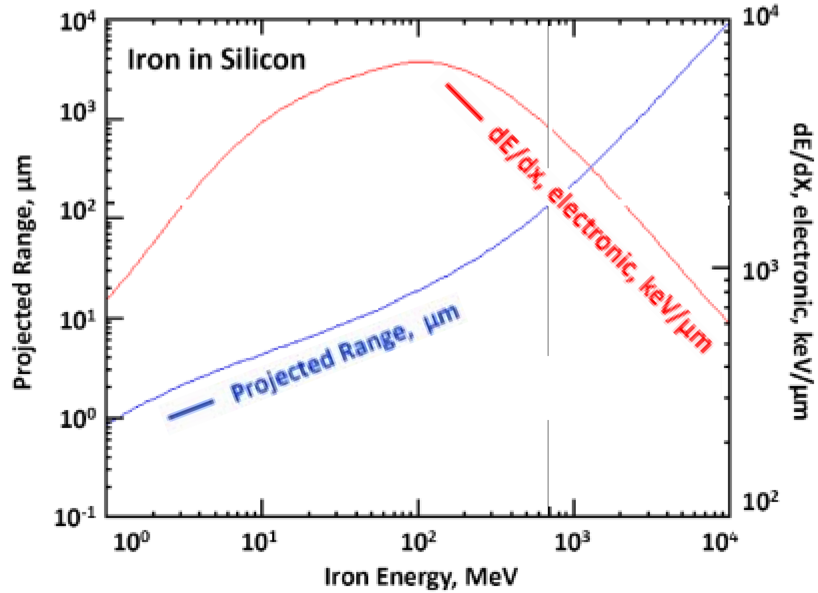
- Principles of Radiation Protection
- Sources of Ionizing Radiation
  - (Galactic) Cosmic Rays
  - Trapped Energetic Particles
  - Solar Particle Events
- Radiation in Past and Current Spaceflight Operations
  - Apollo-era
  - Shuttle and ISS
- Radiation and Future Spaceflight Operations
  - Moon
  - Mars and beyond
- Characterizing the Radiation Environment
  - Observations
  - Forecasting
- Summary

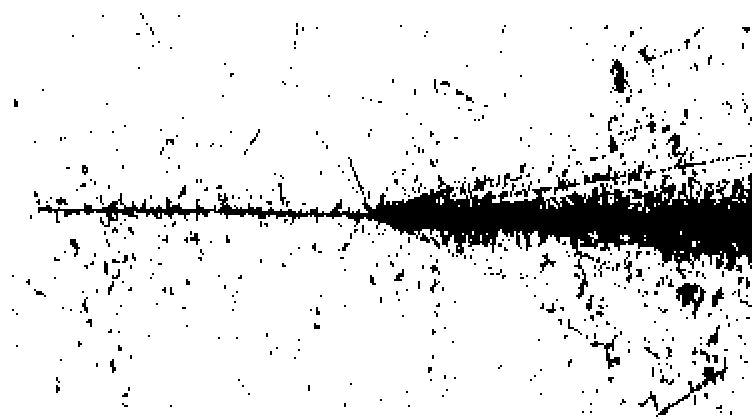
Principles of Radiation Protection

- Radiation of biological concern to the manned program is primarily “ionizing radiation”
- Ionizing radiation is produced by energetic (enough) particles (charged and neutral) or photons with sufficient energy to pass into and through human tissue; for protons, threshold energy is ~10 MeV
  - Protons, α-particles (helium nuclei), heavier ions, β-particles (electrons and positrons)
  - Neutrons
  - X-rays, γ-rays
- These sources ionize matter as they pass through it, and consequently damage human tissue in this interaction

Effects of Ionizing Radiation

- Charged particles loose energy by ionizing the matter they pass through
  - Rate of energy deposition dE/dx (Linear energy transfer LET); Vol II, Ch.3, Eq. 3.11 (the Bethe-Bloch equation)
  - Rate of energy deposition $dE/dx \propto z^2$
  - Also nuclear interactions, fragmentation, showers
  - Damage $\propto$ LET
- Protecting electronics
  - Memory corruption, CPU errors, part failure
- Protecting humans
  - Keep risk from chronic dose low, i.e. lifetime cancer risk due to integrated dose over mission(s) below mandated level
  - Protect against serious injury from acute dose due to prompt radiation from Sun





Iron ion travelling through plastic

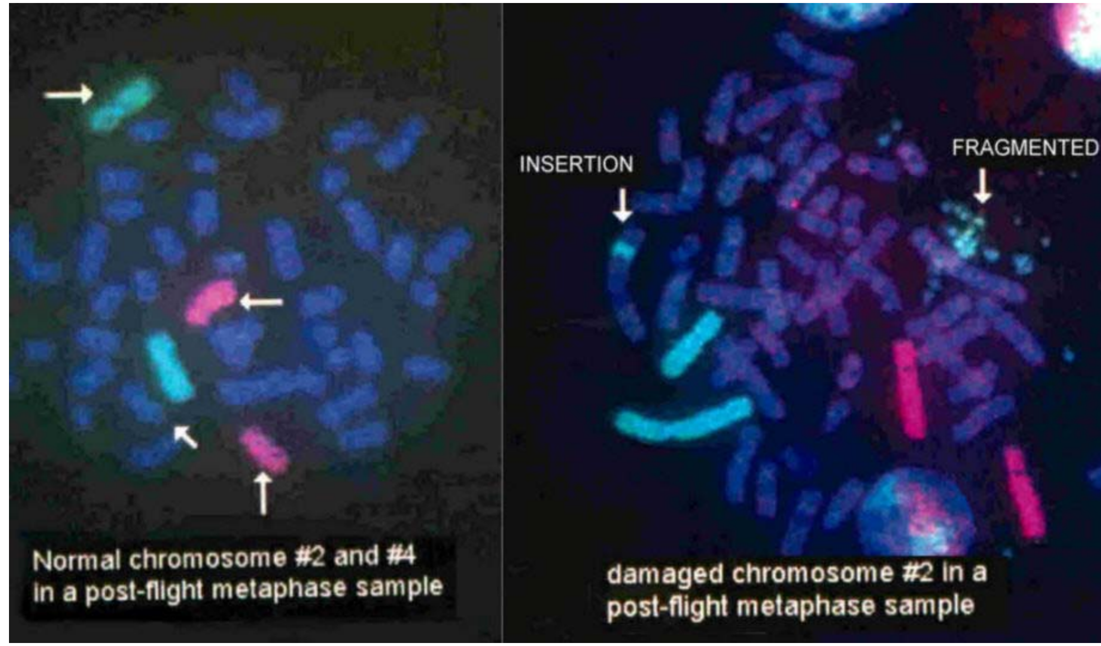
Radiation Units

- Gray (Gy) is the unit which characterizes amount of radiation absorbed by living tissues
- 1 Gy is defined to be 1 Joule of radiation energy absorbed per kilogram of matter (tissue, silicon, aluminum, etc.); 1 rad = 0.01 Gy
- Damage to matter depends on type of radiation (photon versus particle, light versus heavy ion, etc.)
- "Quality" factor (Q) used to quantify degree by which absorbed radiation produces damage, i.e., relative biological effectiveness (RBE) of any dose of radiation
- Dose equivalent is measured in sieverts (Sv) or rem (1 rem = 0.01 Sv) → rem = Q x rad; Sv = Q x Gy
- Q is determined empirically, normalized to damage produced by γ-rays (Q=1.0), for the same dose

Why Characterize Radiation Sources?

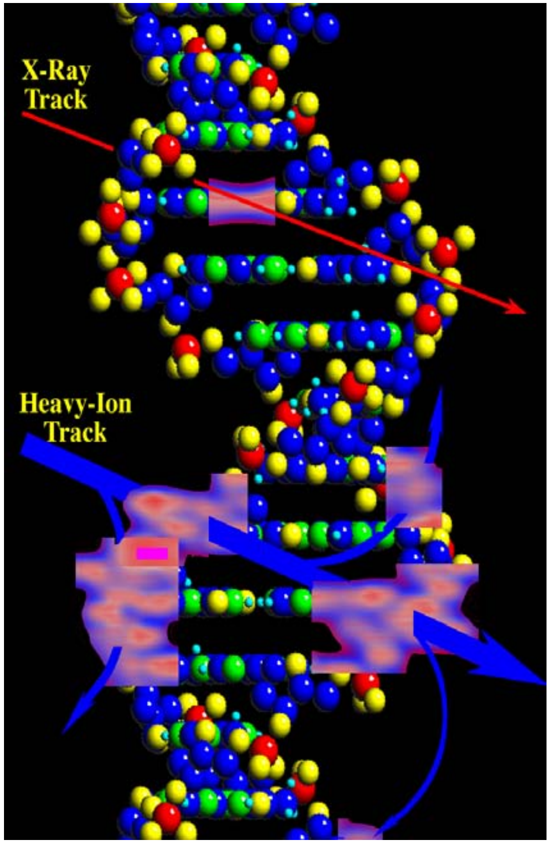
To understand risks to:

- Astronauts
  - Radiation Poisoning from sudden events
  - Heightened long-term risk
    - Cancer
    - Cataracts
- Spacecraft examples
  - Single event upsets
  - Attitude (Sun pulse & star tracker)
  - Radiation damage



Challenges to Radiation Protection

- Protect astronauts and equipment during transit to and habitation of lunar surface
  - Understand the lunar environment, optimize shielding design, accurate predictions of biological effect
- Primary spectrum of radiation is variable (time, energy, composition)
- Effect depends on properties of the radiation
  - Total energy deposited in the body
  - Rate of radiation dose
  - Particles with higher rate of energy deposition dE/dx may do more damage ($dE/dx \sim z^2$)
  - Particles fragment/scatter (focused damage)



(Courtesy, Mark Weyland, NASA Johnson Space Center, Space Radiation Analysis Group)

Threats of Radiation – "LNT"

- For large known radiation doses (i.e., Hiroshima and Nagasaki victims), linear statistical relationship exists between cancer mortality and dose
- Cancer occurs also naturally without specific large radiation dose, so establishing relationships at low dose difficult
- ICRP adopted Linear No-Threshold (LNT) model in 1959
  - Conservative model which extrapolates low dose threats linearly from high dose effects
  - Ignores statistical fluctuations which may dominate at low dose
  - Underscores the point that any amount of ionizing radiation poses a risk

Threats of Radiation – Hormesis and ALARA

- Hormesis is controversial notion that is counter to LNT suggesting that some low does of radiation are actually beneficial – generally not accepted
- Radiation exposure is prudently managed through the ALARA principle: As Low As Reasonably Achievable.
  - In the lab this means, for instance, limiting time of exposure, providing suitable shielding, and maximizing distance from a radioactive source
  - In space, this might mean limiting lifetime mission time, forgoing an EVA, or seeking shielding shelters
- NASA ALARA program seeks to prevent short-term flight risks and long-term risks to astronauts balancing moral obligations and financial realities

Threats of Radiation – National and International Regulatory Structures

- ICRP (International Commission on Radiological Protection)
- ICRU (International Commission on Radiation Units)
- NCRP (National Council on Radiation Protection)
- IEEE (Institute of Electrical and Electronics Engineers)
- NRC (US Nuclear Regulatory Commission)
- DOE (Department of Energy)
- OSHA (Occupational Safety and Health Administration)

Integrated Risk Projection

Mitigation:

- Shielding materials
- Radioprotectants
- Pharmaceuticals

Space Radiation Environment

↓

Radiation Shielding

↓

Initial Cellular and Tissue Damage
DNA breaks, tissue microlesions

↓

DNA repair, Recombination,
Cell cycle checkpoint, Apoptosis, Mutation,
Persistent oxidative damage, & Genomic Instability

↓

Tissue and Immune Responses

↓

Risks:
Chronic: Cancer, Cataracts,
Central Nervous System,
Heart Disease
Acute: Lethality, Sickness,
Performance

Risk Assessment:

-Dosimetry
-Biomarkers
-Uncertainties
-Space Validation

$Risk_j$ (age,sex,mission)

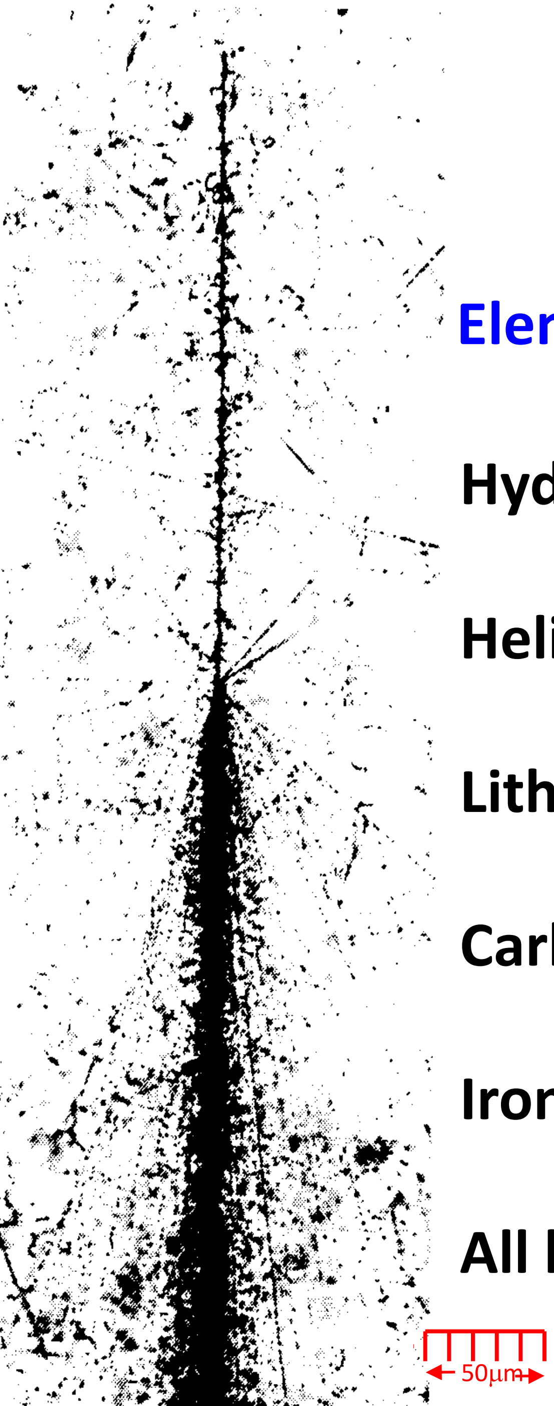
Sources of Ionizing Radiation: Cosmic Rays

Ray Liotta:
A star,
but not
cosmic

Ray Romano:
A comic Ray, not
a cosmic ray

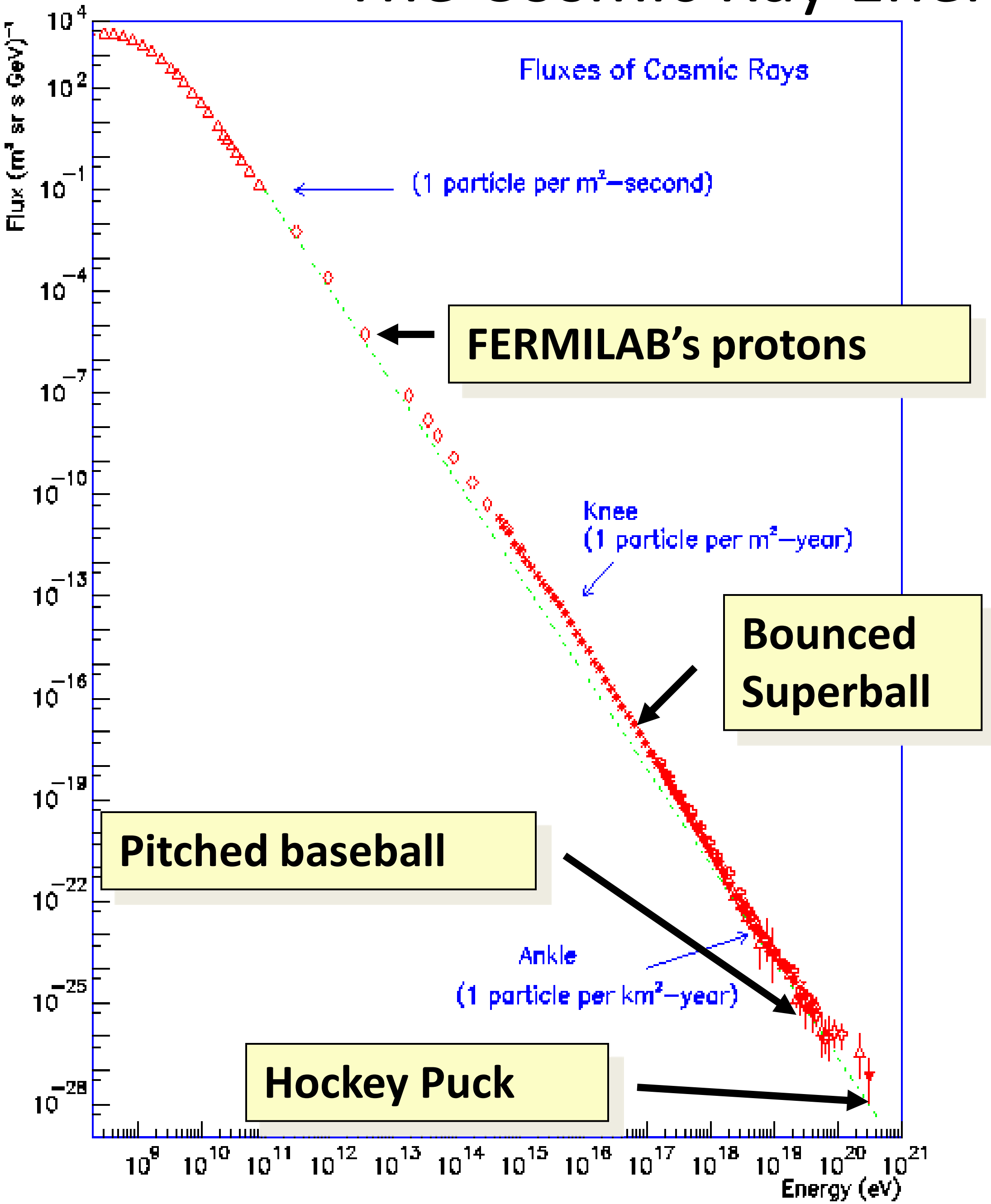
"Ray" Lopez:
is cosmic, but is
really Ramon…

Energetic Charged Particles



Element	Atomic Number (Z)	Solar System Composition (relative #)	Primary Cosmic Ray Flux ($\#/m^{-2}$ sec)
Hydrogen (H)	**1**	**1.00**	**640**
Helium (He)	**2**	**6.8×10^{-2}**	**94**
Lithium, Beryllium, Boron		**2.6×10^{-9}**	**1.5**
Carbon, Nitrogen, Oxygen		**1.2×10^{-3}**	**6**
Iron (Fe)	**26**	**3.4×10^{-5}**	**0.24**
All heavier atoms		**1.9×10^{-6}**	**0.13**

The Cosmic Ray Energy Spectrum



The highest energy Cosmic Rays are SUBATOMIC particles carrying the energy of MACROSCOPIC objects!

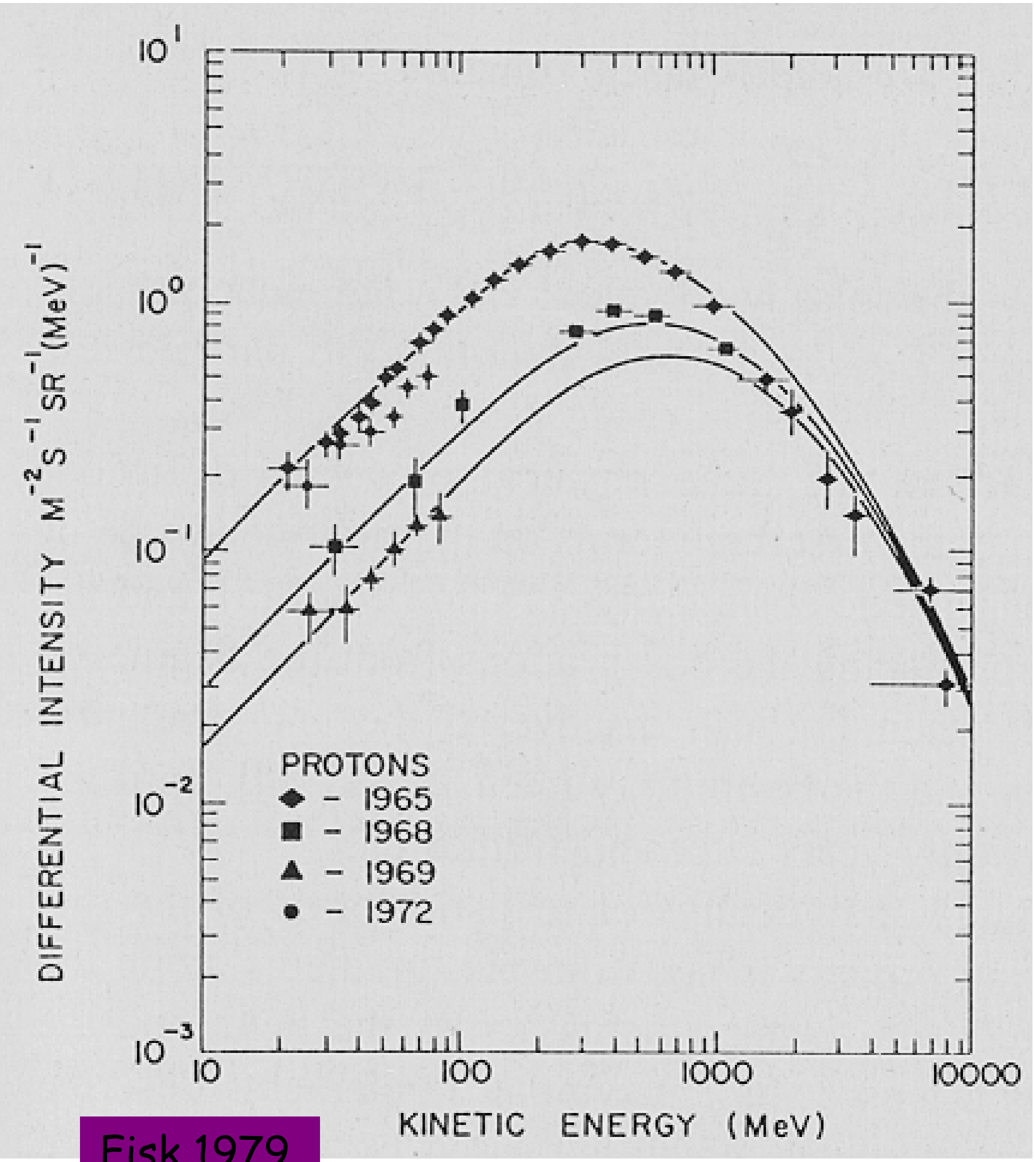
4×10^{21} eV = 60 joules

>***<u>10 MeV p+'s</u>*** penetrate typical s/c shielding and pose energy deposit risks in man and machine

Galactic Cosmic Rays in the Heliosphere

Proton energy spectra observed at 1 AU (1965, solar minimum and 1969, maximum)

High-energy ions coming from the galaxy (thought to originate in association with supernovae remnants) penetrate the inner heliosphere.

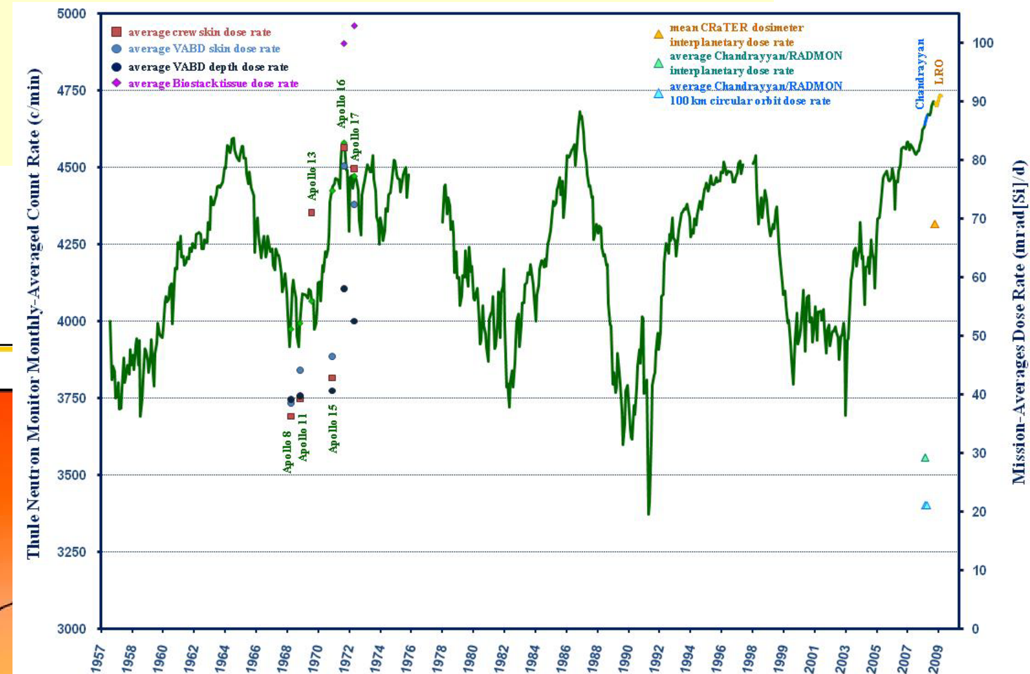


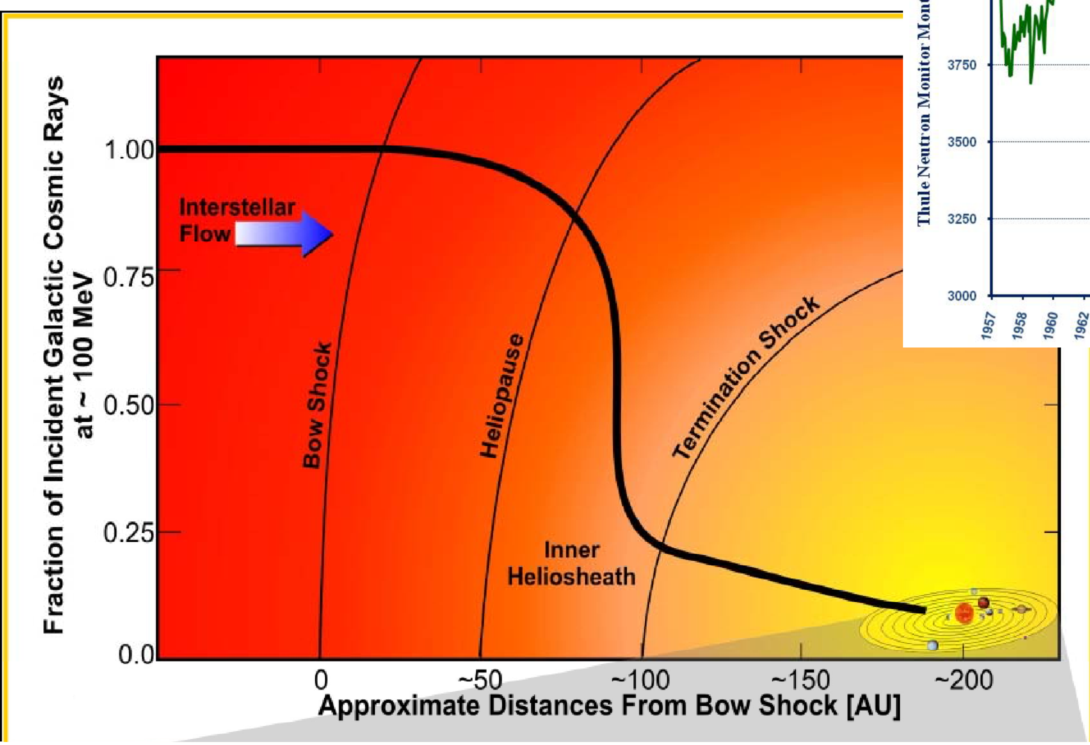
Fisk,1979

Galactic Cosmic Ray Modulation

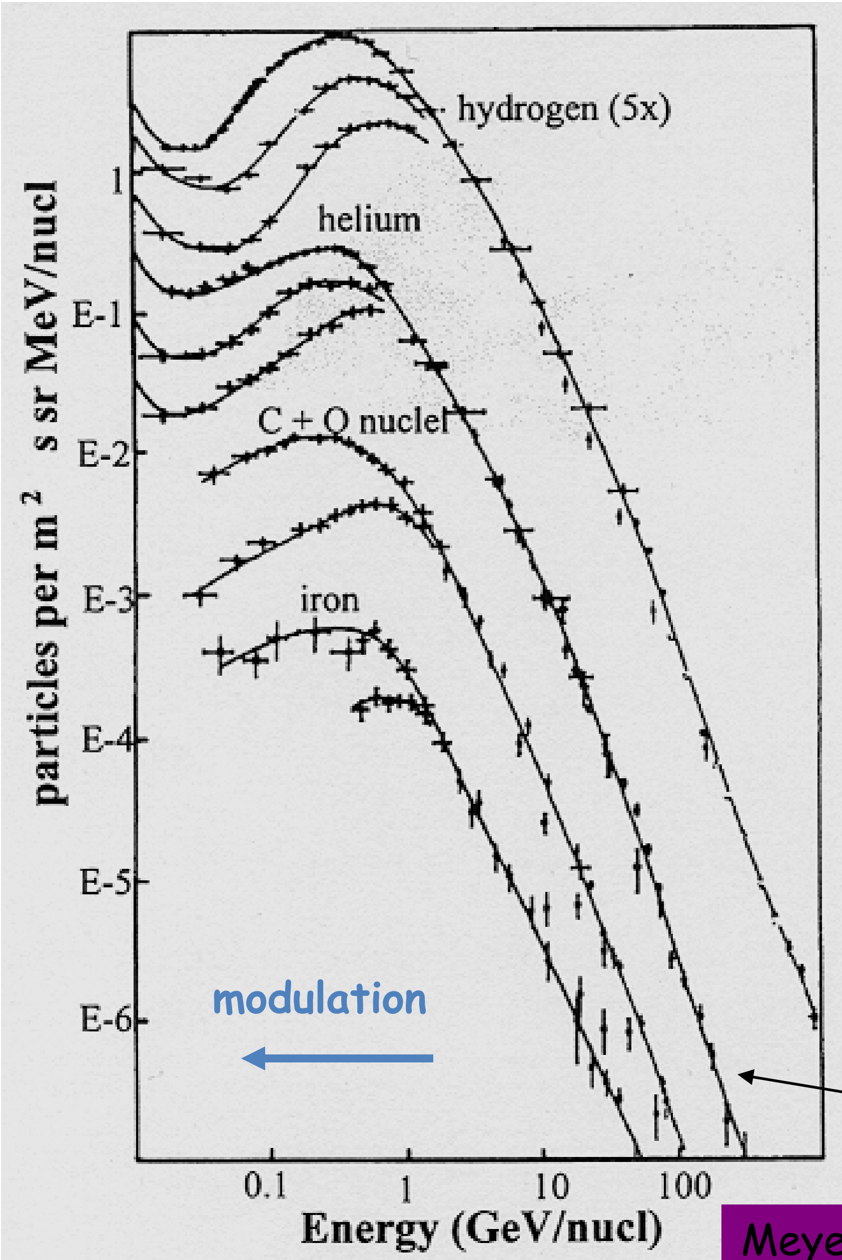
Interactions with solar wind and interplanetary magnetic field lead to:

- Radial intensity gradients
- Temporal variations



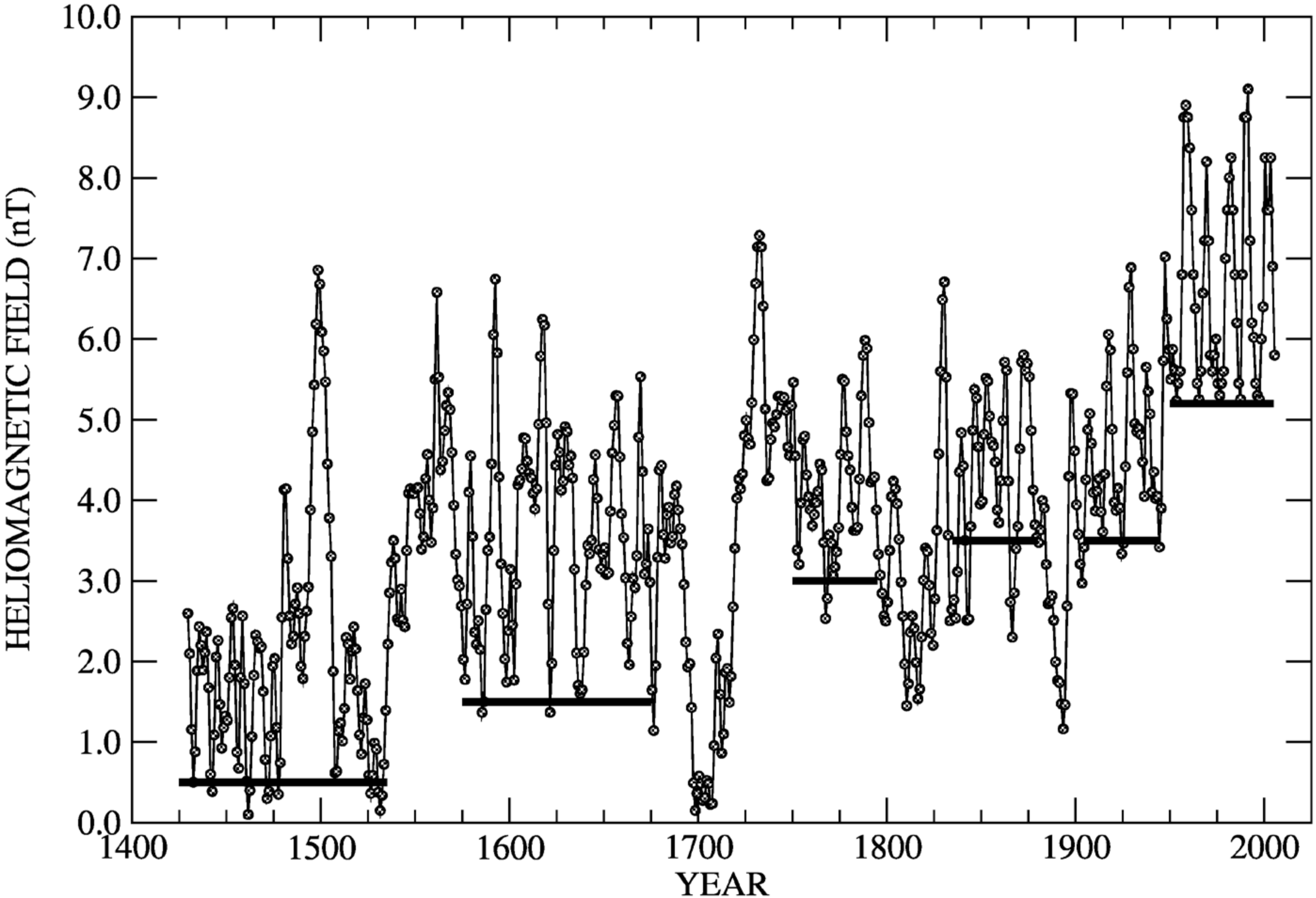


Galactic Cosmic Rays - composition

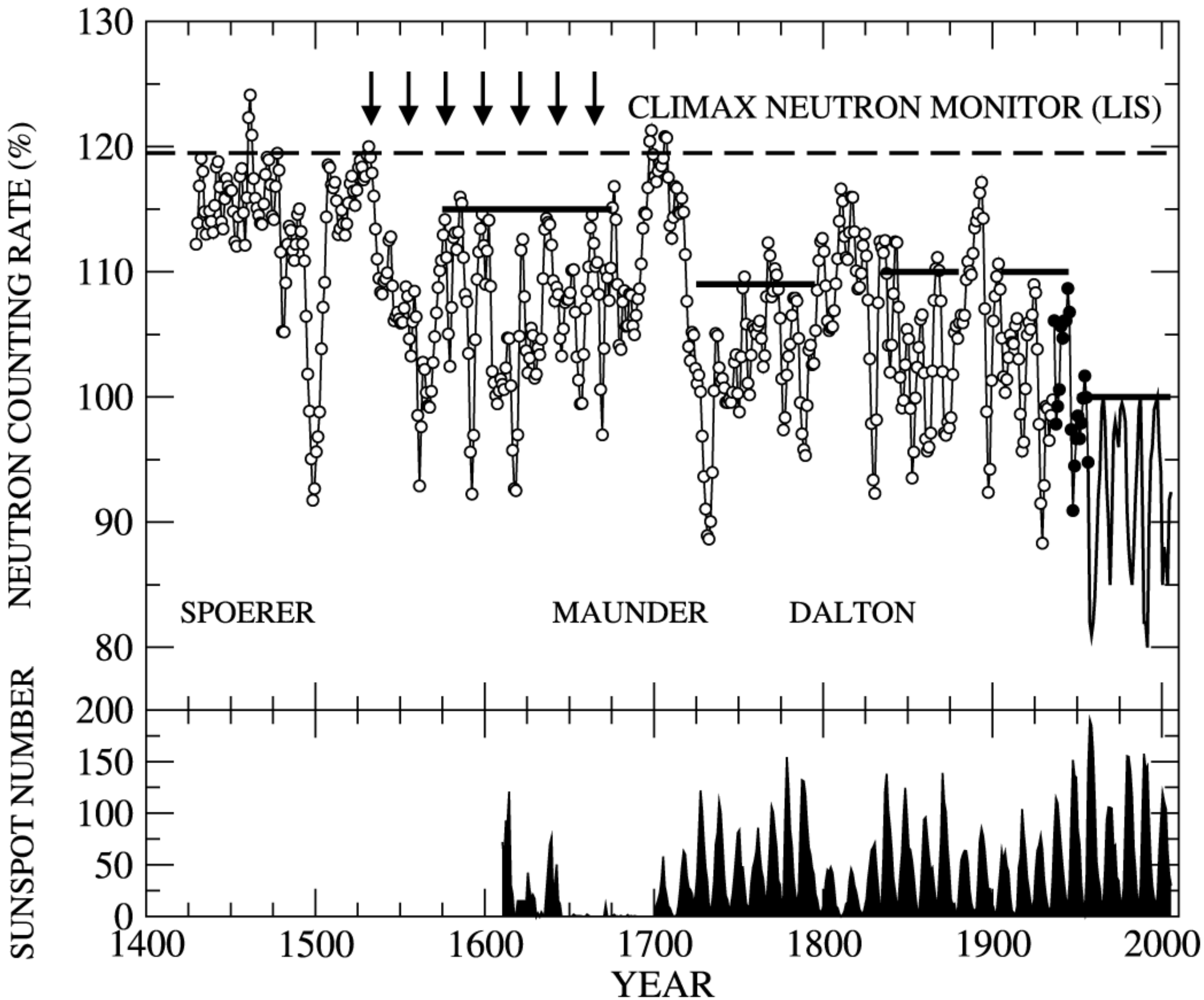


Meyer et al., 1974

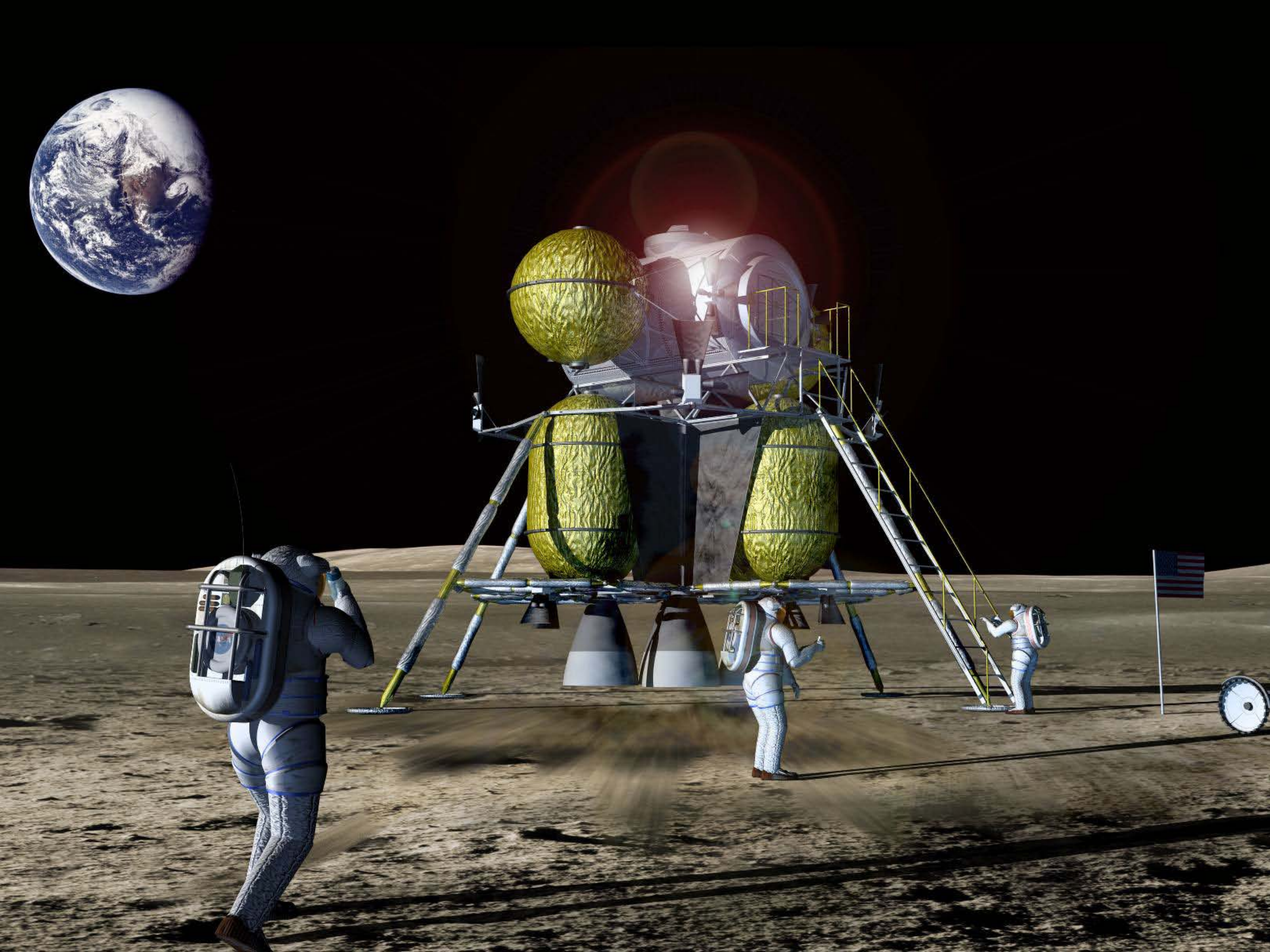
$J \sim E^{-\gamma}$ with $\gamma = -2.5$



- Heliospheric magnetic field helps limit access of cosmic rays to inner solar system
- Some studies show that we are at 500-year maximum of field strength
- Stronger fields provide greater shielding, hence 500-year minimum in GCR intensity



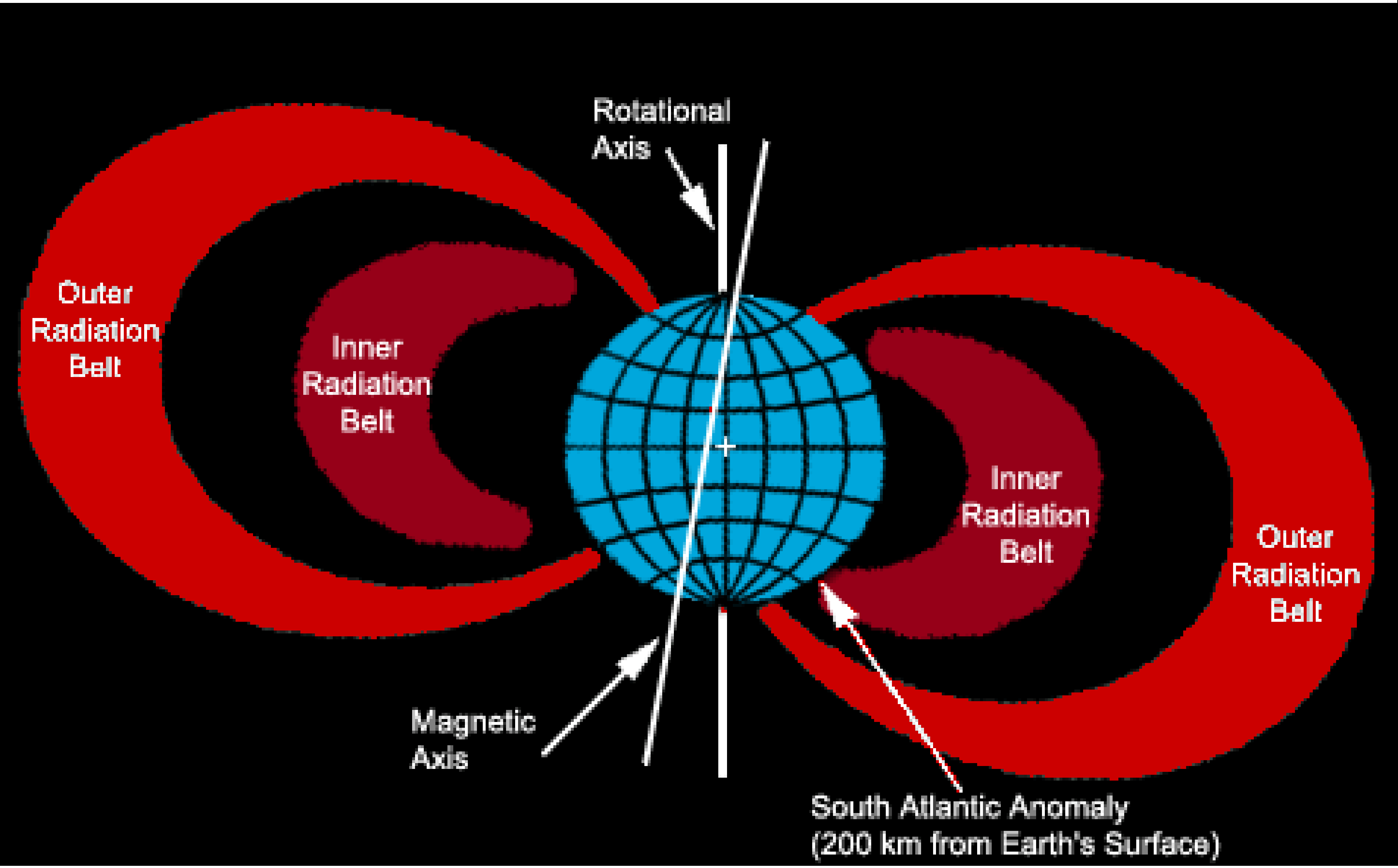
- Other studies based on ice core records suggest that we are indeed near a 500-year minimum in GCR intensity, with historic rates more than 20% greater than present



Sources of Ionizing Radiation: Trapped Particles

- Planetary magnetospheres with strong dipolar magnetic fields (i.e., Earth, Jovian planets) can trap charged particles (bottle) as well as deflect them (shield); ordered by magnetic field geometry
- Trapped energetic particles (principally protons and electrons, but also heavy ions) fill vast regions of the inner magnetosphere in the Van Allen "Radiation" Belts
  - Belts are not "radioactive", rather, they contain particles capable of producing ionizing radiation
  - Protons dominate inner belt; electrons outer belt
- Earth's offset tilted dipole brings radiation belts closest to surface off Brazil and produces region called the South Atlantic Anomaly (SAA) – a region where inner belt protons affect LEO missions
- Beyond LEO, missions going to Moon and beyond pass rapidly through radiation belts (ALARA) , thus minimizing radiation risks

South Atlantic Anomaly

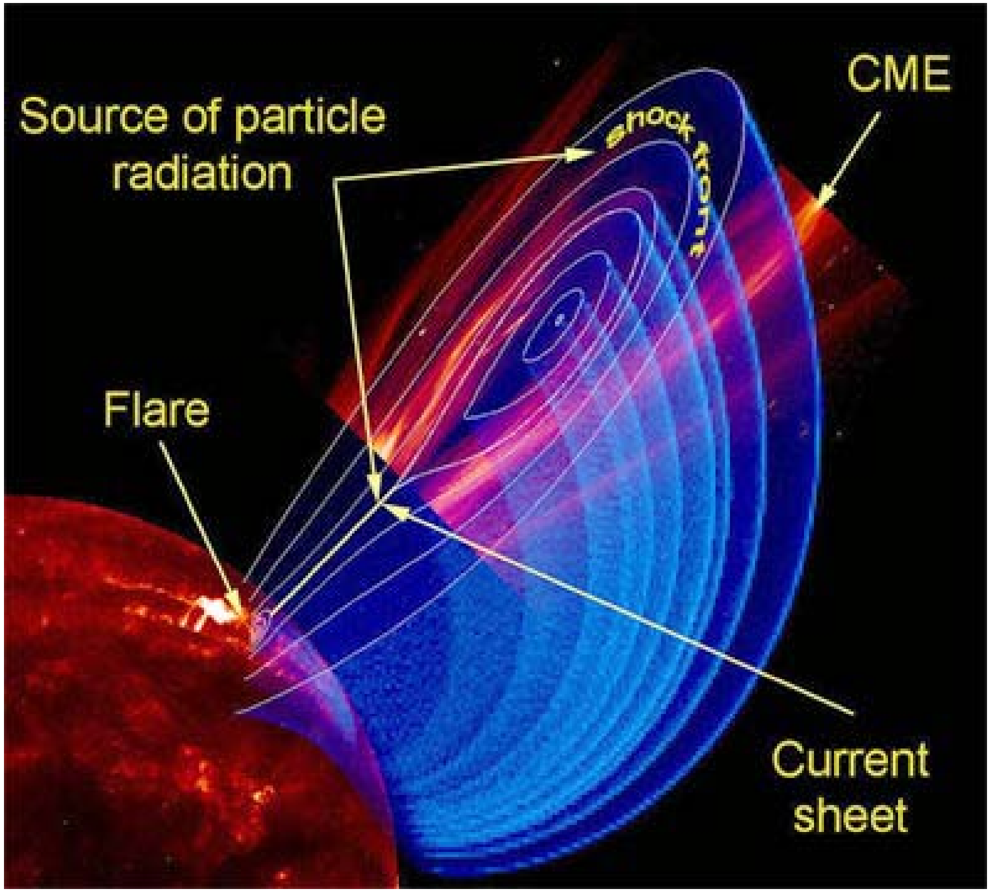


Sources of Ionizing Radiation: Solar Particle Events

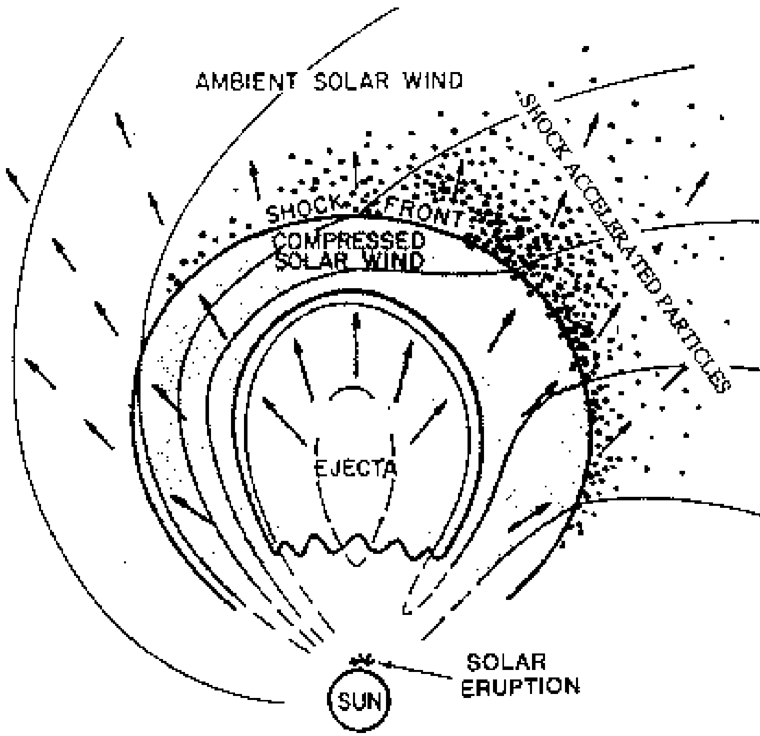
- Solar Energetic Particles (SEPs) are energetic particles accelerated by processes associated with a solar source

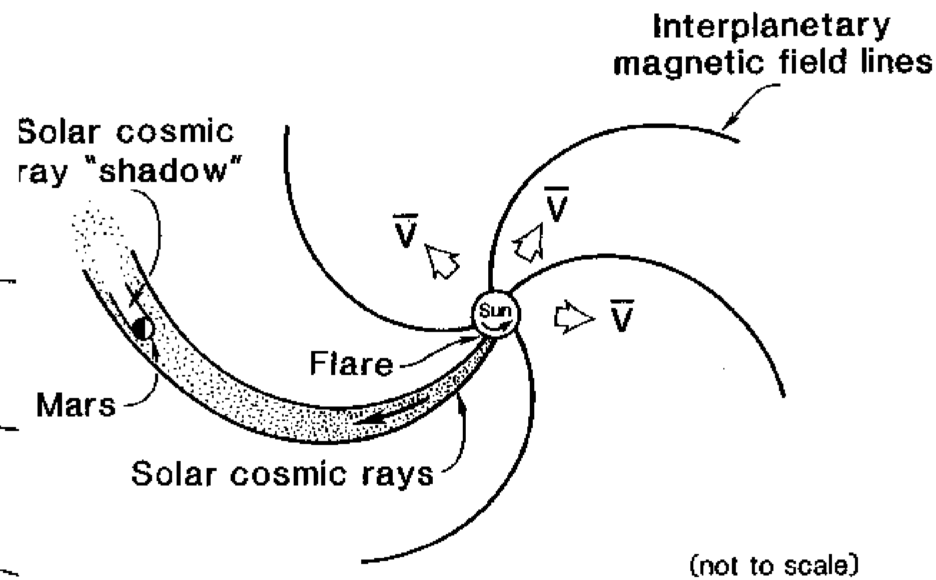
- SEPs originate from:
  - acceleration near a solar flare site; and
  - acceleration through interactions with interplanetary shock waves propagating away from the Sun

Sites of SEP Creation



Illustrations of ICME shock SEP and flare SEP (with no CME) events - Sometimes these are mixed together – predictive modeling is HARD!

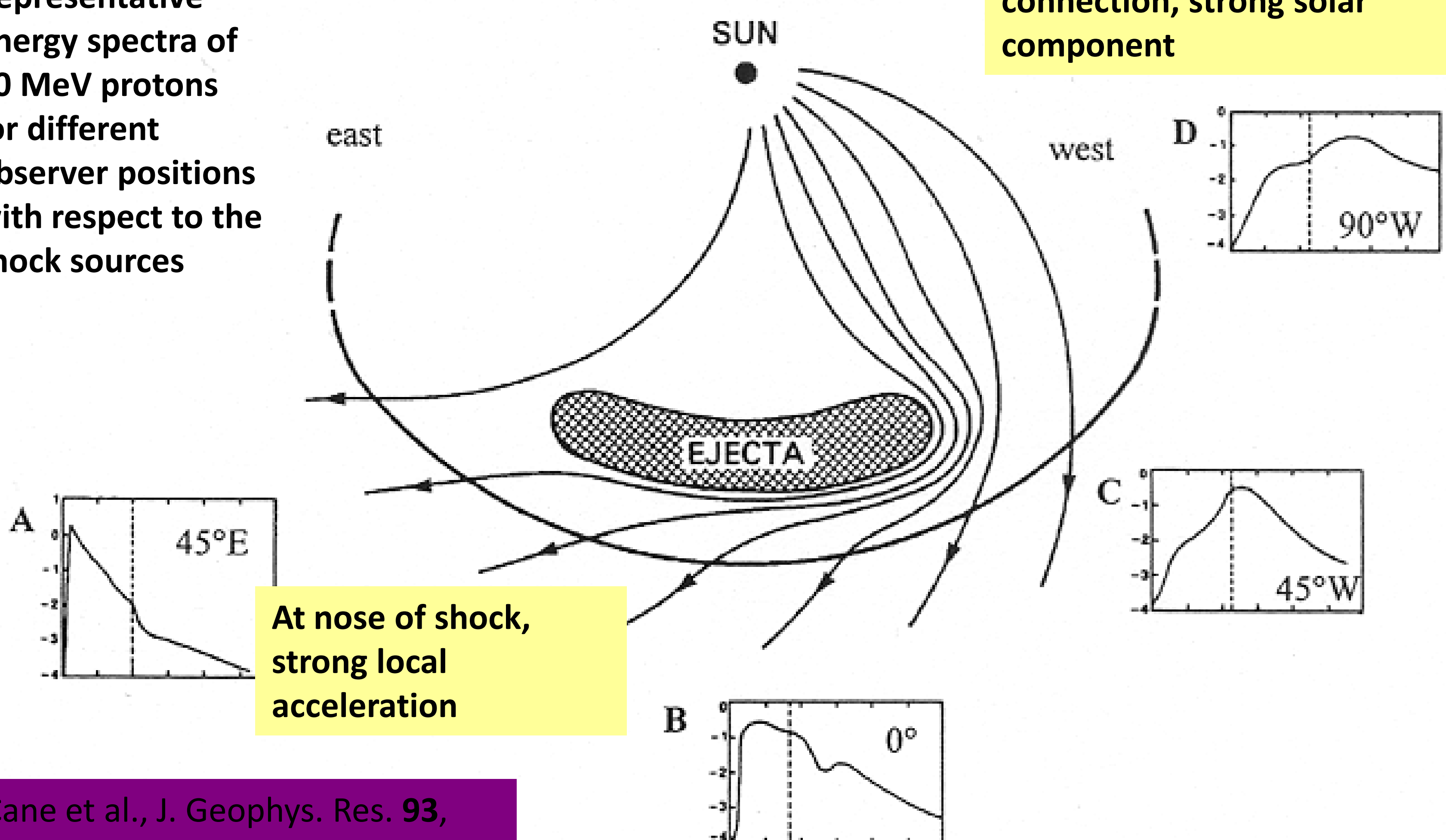




SEPS spectra and intensity vary w/ magnetic connectivity to source

Representative energy spectra of 20 MeV protons for different observer positions with respect to the shock sources

Flank of shock, but flare site connection, strong solar component



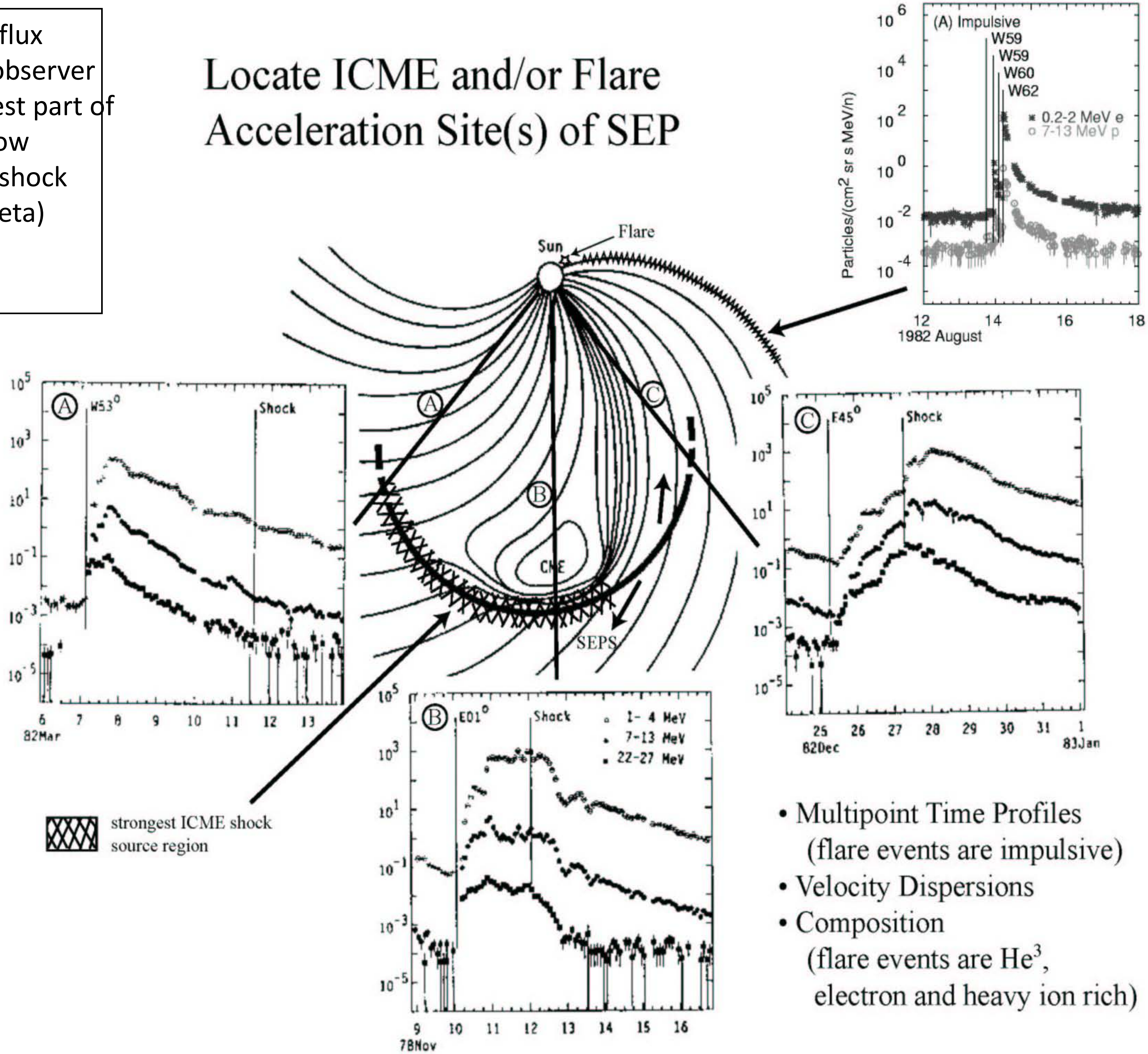
At nose of shock, strong local acceleration

Cane et al., J. Geophys. Res. **93**, 9555, 1988

The timing of the peak flux depends on when the observer connects to the strongest part of the shock – need to know physical parameters of shock (Θ_{BN}, Mach #, plasma beta)

Locate ICME and/or Flare Acceleration Site(s) of SEP

Time of Arrival, Amplitude, and Duration of SEP critically important to users



- Multipoint Time Profiles (flare events are impulsive)
- Velocity Dispersions
- Composition (flare events are He^3, electron and heavy ion rich)

Practical Motivation: Drivers of Space Weather

Coronal Mass Ejections (CMEs):
- Arrive 1- 4 Days later
- Last a day or two
- Produce Geomagnetic Storms at Earth
- Systems Affected
  - Radio Communications
  - Navigations
  - Electric Power Grids
  - Pipelines

Solar X-Rays:
- Arrive in 8 Minutes
- Last minutes to hours
- Increases ionosphere density
- Systems Affected:
  - Radio Communications
  - Navigation

High-Speed Solar Wind:
- Common During Solar Minimum
- Enhances Radiation Belts
- Systems Affected
  - Satellite Charging
  - Astronouts

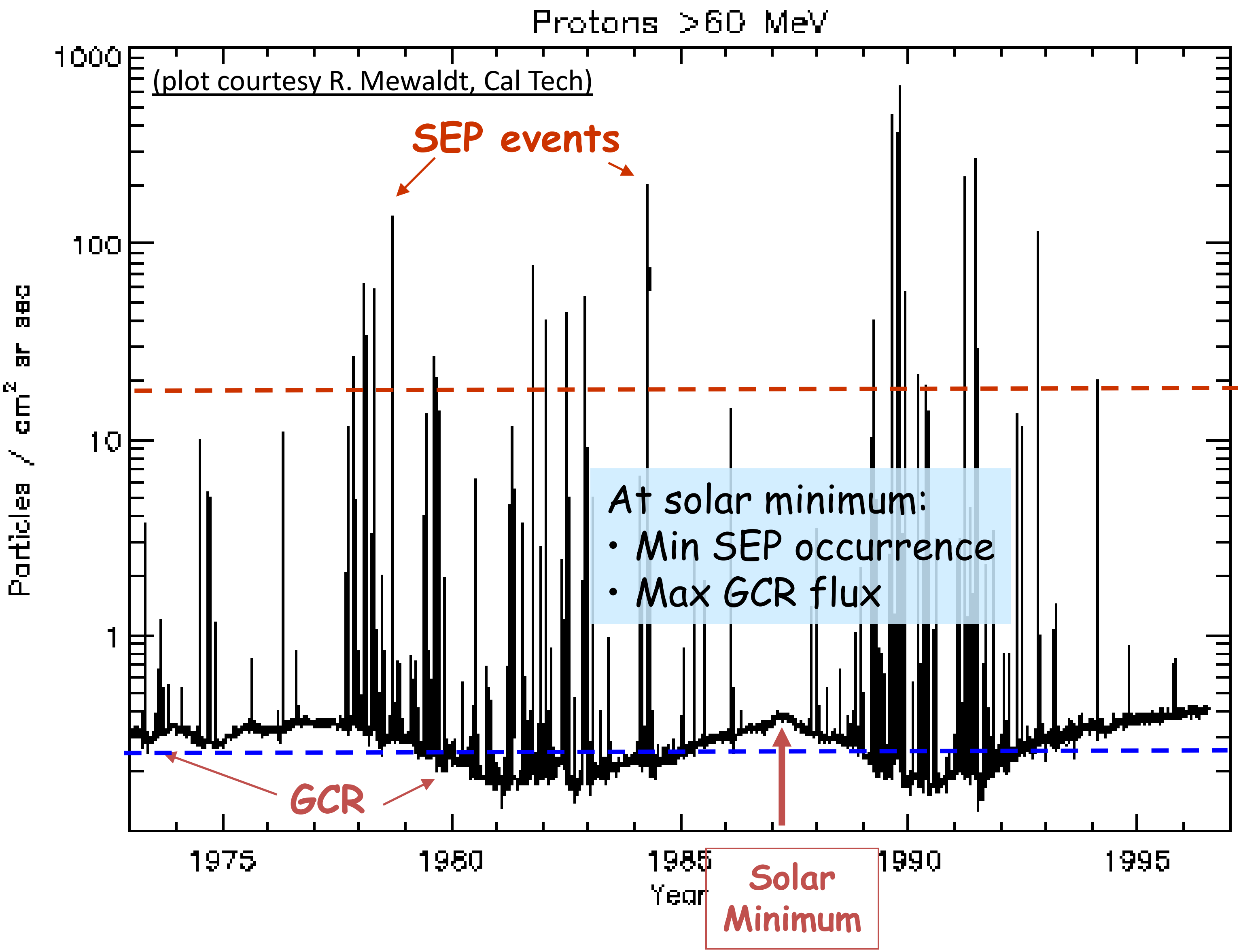
Solar Energetic Particles:
- Arrive in 30 Minutes to 24 hours
- Last several days
- Systems Affected:
  - Astronauts
  - Spacecraft
  - Airlines
  - Radio Communications

Solar Radiation Storms (Energetic Particles)

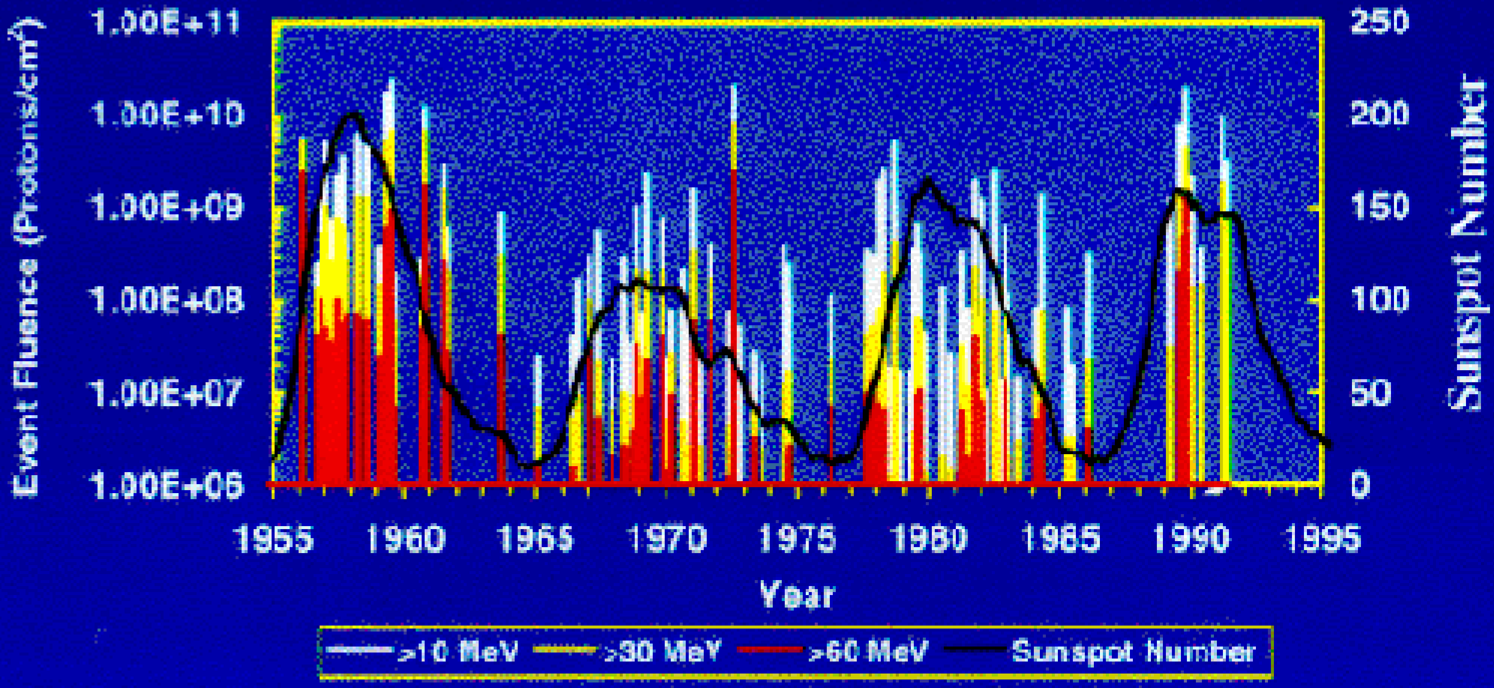
	Solar Radiation Storms	Flux level of >10 MeV protons $(cm^2\ s\ sr)^{-1}$	Frequency of Occurrence
Extreme **S5**	**Biological:** unavoidable high radiation hazard to astronauts on EVA (extra-vehicular activity); high radiation exposure to passengers and crew in commercial jets at high latitudes (approximately 100 chest x-rays) is possible. **Satellite operations:** satellites may be rendered useless, memory impacts can cause loss of control, may cause serious noise in image data, star-trackers may be unable to locate sources; permanent damage to solar panels possible. **Other systems:** complete blackout of HF (high frequency) communications possible through the polar regions, and position errors make navigation operations extremely difficult.	10^5	Fewer than 1 per cycle
Severe **S4**	**Biological:** unavoidable radiation hazard to astronauts on EVA; elevated radiation exposure to passengers and crew in commercial jets at high latitudes (approximately 10 chest x-rays) is possible. **Satellite operations:** may experience memory device problems and noise on imaging systems; star-tracker problems may cause orientation problems, and solar panel efficiency can be degraded. **Other systems:** blackout of HF radio communications through the polar regions and increased navigation errors over several days are likely.	10^4	3 per cycle
Strong **S3**	**Biological:** radiation hazard avoidance recommended for astronauts on EVA; passengers and crew in commercial jets at high latitudes may receive low-level radiation exposure (approximately 1 chest x-ray). **Satellite operations:** single-event upsets, noise in imaging systems, and slight reduction of efficiency in solar panel are likely. **Other systems:** degraded HF radio propagation through the polar regions and navigation position errors likely.	10^3	10 per cycle
Moderate **S2**	**Biological:** none. **Satellite operations:** infrequent single-event upsets possible. **Other systems:** small effects on HF propagation through the polar regions and navigation at polar cap locations possibly affected.	10^2	25 per cycle
Minor **S1**	**Biological:** none. **Satellite operations:** none. **Other systems:** minor impacts on HF radio in the polar regions.	10	50 per cycle

SEP event occurrence varies with the solar cycle in anti-phase with weaker but persistent galactic cosmic ray fluxes

When is it safe for space travel? Never!!



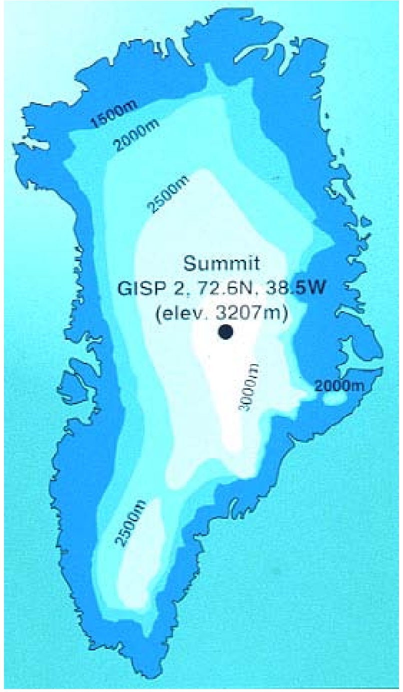
Significant Solar Proton Episodes Since 1955

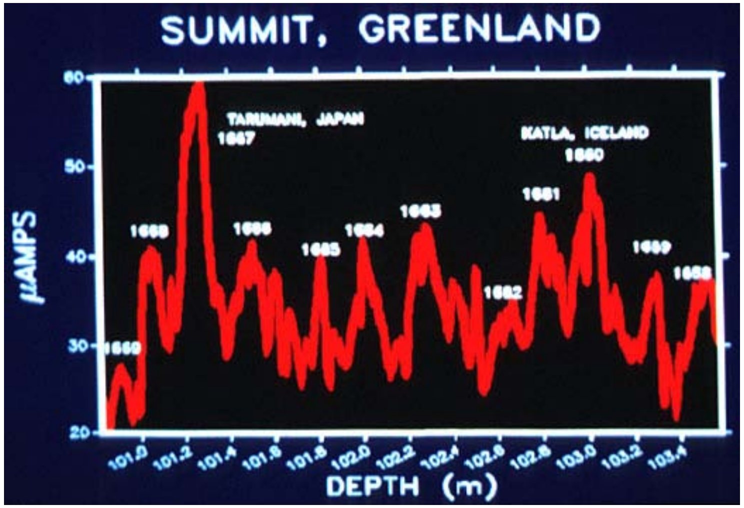


But what about before the start of the space age? What's the largest the Sun can throw our way? Ice cores may provide an answer…

Figure courtesy of Ron Turner, ANSER

Unraveling the Past History of Cosmic Rays with Arctic Ice

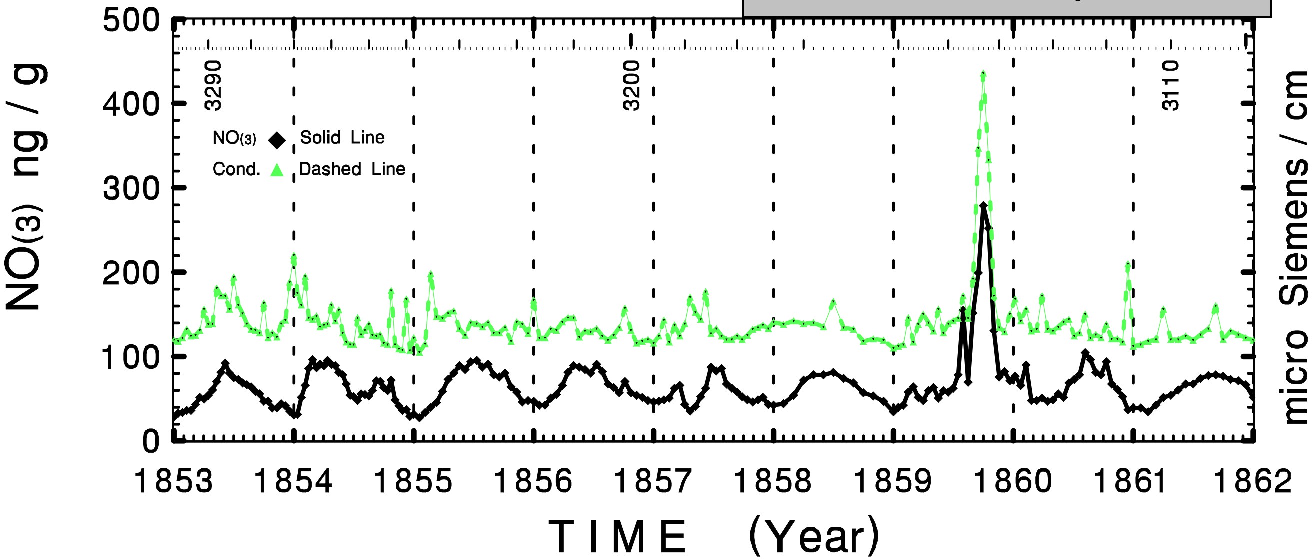




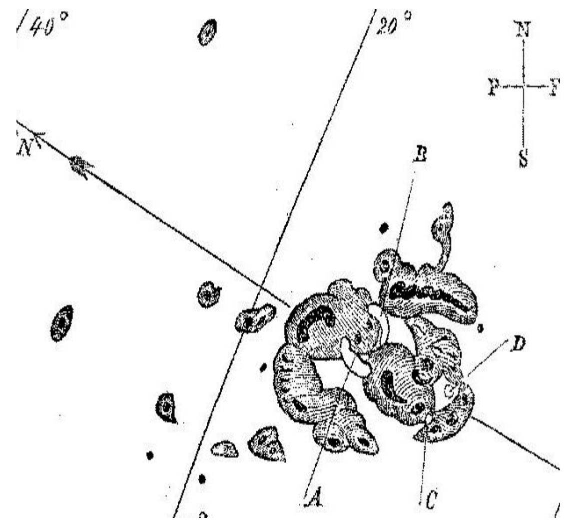
Solar Cause and Terrestrial Effect?

***Terrestrial Effect?*: Polar ice core nitrate "spike"**

***Solar Cause?*: Major solar event from recent history – Carrington white-light flare of 1859**



Example of high-resolution nitrate concentrations (black curve in ng g^{-1}) and electrical conductivity (green curve in mSiemens cm^{-1}) from the Greenland ice core. The large impulsive event at 1859.75 is the largest such event in the period 1561-1991 and occurs in close correlation to the extremely rare 1 September 1859 "white light" flare observed by Carrington (1860). (Taken from Shea and Smart, 2003)[18]



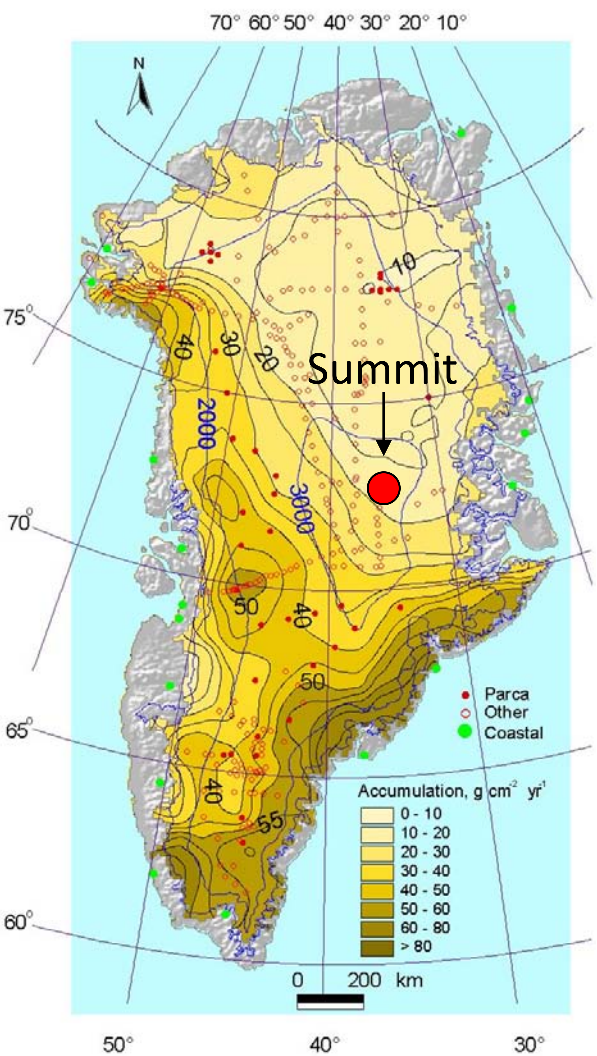
Reproduction of a drawing by R.C. Carrington, showing the location of the flare he observed serendipitously while making a routine drawing of an active sunspot region of the Sun. Reproduced from his 1860 paper in Monthly Notices of the Royal Astronomical Society (vol. 20, p. 13). (After "Great Moments in Solar Physics", P. Charbonneau, NCAR, 2000)[1]

Proposed physical mechanism:

- **Energetic protons generated during impulsive solar events**
- **>30 MeV solar protons penetrate deep into stratosphere where ozone is "burned" and nitrates are produced**
- **Solar-proton-generated nitrates precipitate and are incorporated into stratified ice sheet chronology**

Drilling of Ice Cores (mid-June 2004) to Return to US (late-June 2004)

Our target-of-opportunity cores result from a project needing only bore holes at Summit, Greenland (special thanks to Sarah Das, WHOI, Joe McConnell, DRI, and Jane Dione, NSF for their help in getting these cores for our project).

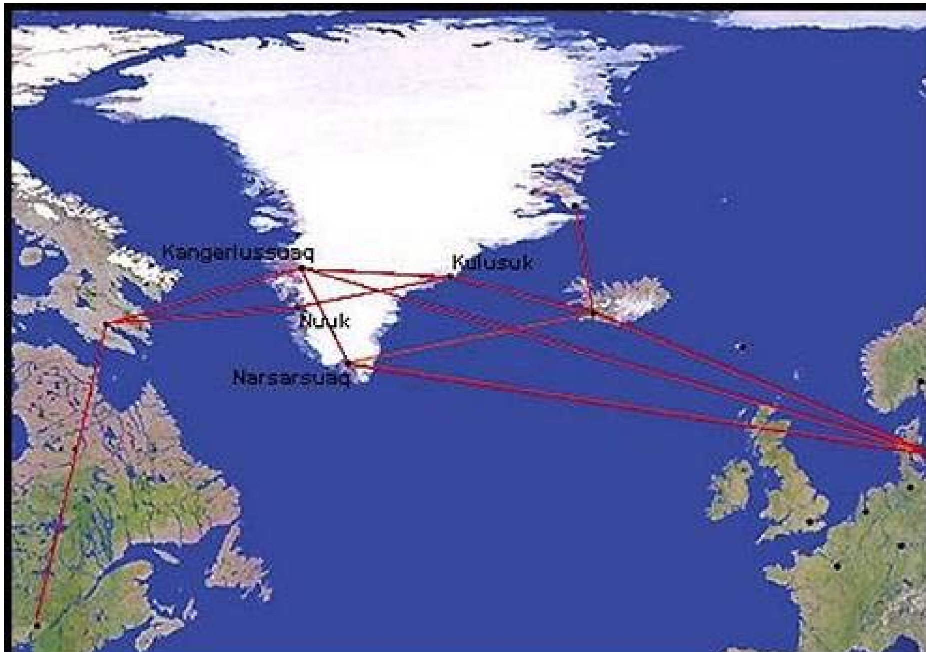


Ice sheet accumulation 1971-90 (Bales et al., GRL, 28:2967-70, 2001)

Jay Kyne drilling an ice core on another expedition to Greenland in summer 2003

Two proximate 30-meter-deep cores were finished on June 9th at Summit, Greenland by Jay Kyne, a driller with Ice Core Drilling Services, using a 4" "SideWinder" drill.

Cores were bagged, tubed, boxed, and then transported from Greenland to Scotia, NY via a LC-130 Hercules USAF transport plane.



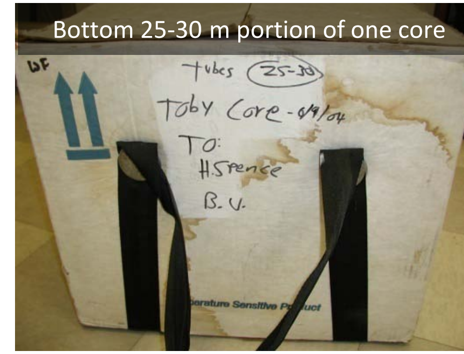
Ice cores arrive at Stratton Air National Guard Base on June 26th. Courier meets plane and transports ice in freezer truck to BU's Medical Campus.

Delivery of Ice Cores (late-June 2004) to First Analysis (early-December 2004)

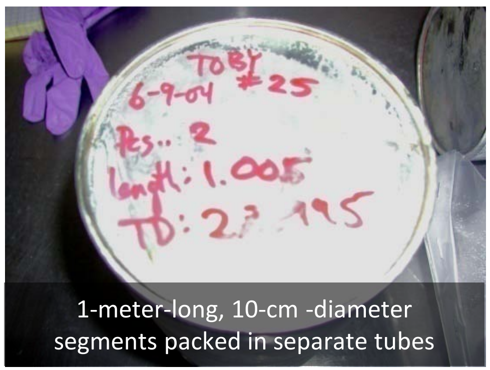

Cores arrive in freezer truck on June 26th


Loading dock at BU Medical Campus


Ten boxes of ice core stored at -30C in large walk-in freezer

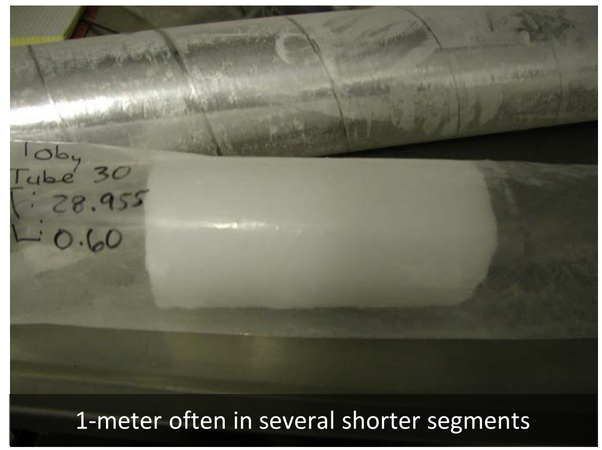


Bottom 25-30 m portion of one core



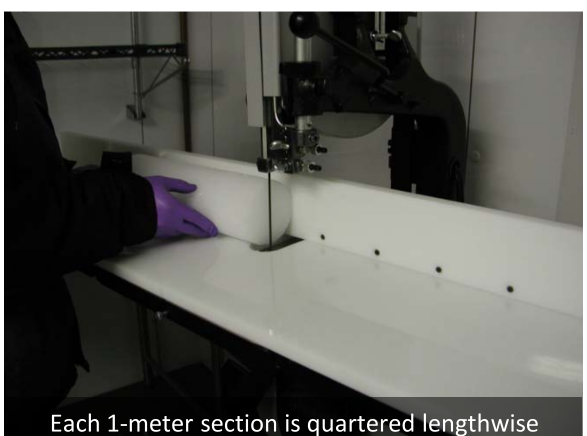
1-meter-long, 10-cm -diameter segments packed in separate tubes

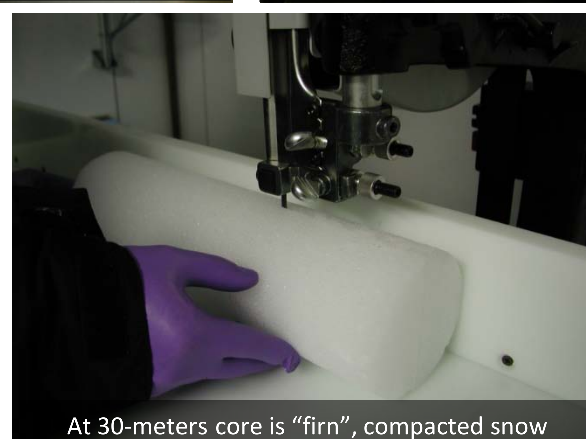

Cores bagged in field; note “this-end-up” arrow

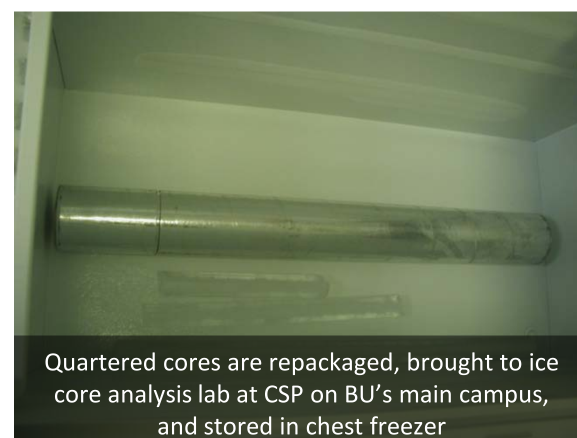


1-meter often in several shorter segments


Cores cut with band saw in cold room


Each 1-meter section is quartered lengthwise

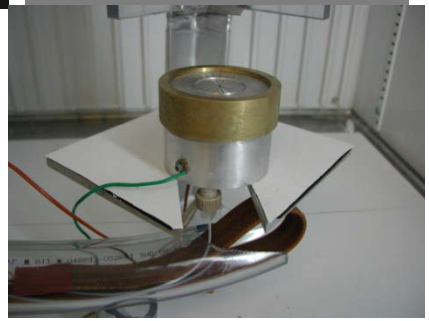

At 30-meters core is “firn”, compacted snow


Quartered cores are repackaged, brought to ice core analysis lab at CSP on BU’s main campus, and stored in chest freezer

Continuous Flow Analysis Laboratory Set-up (December 2004)

Lucite stand inside commercial, upright freezer holds ice cores vertically during continuous melt

Firn melter temperature controlled by heaters w/ active feedback



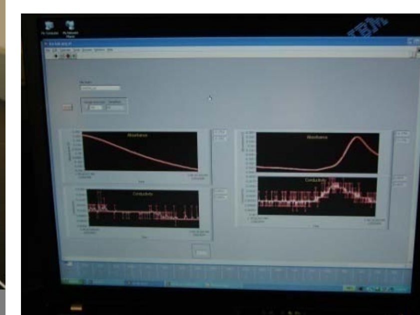
Inner ring melts clean ice; outer ring collects waste water. Capillary slits minimize upward wicking

Melt water is pumped out of freezer for analysis; depth of core is recorded during each melt

Multichannel peristaltic pump provides throughput. Carrier and reagent is mixed with meltwater for nitrate analysis. Pure portion of melt is diverted to conductivity meter.

Meltwater with eluents pass through cadium reaction column before nitrate analysis.

Spectrophotometer measures nitrate concentration in continuous flow at high time cadence with resolution less than 1 ppb



Outputs of spectrophotometer and conductivity meter are digitized and stored on a PC with realtime display via a LabView interface

Large, Historic "GLE"s Show Promising Correlation – Technique and Causality Being Affirmed

Three Unusual Cosmic-Ray Increases Possibly Due to Charged Particles from the Sun

SCOTT E. FORBUSH
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October 10, 1946

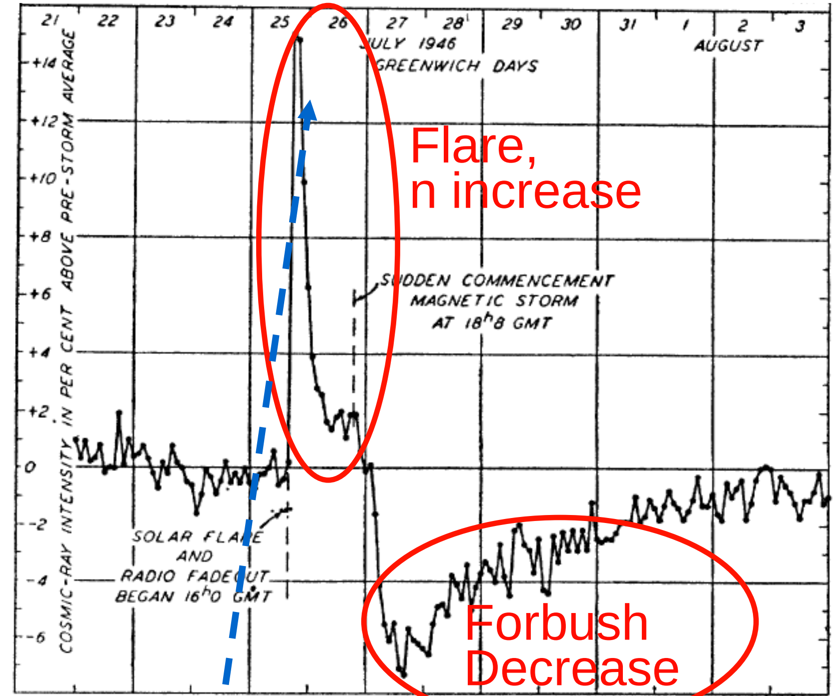
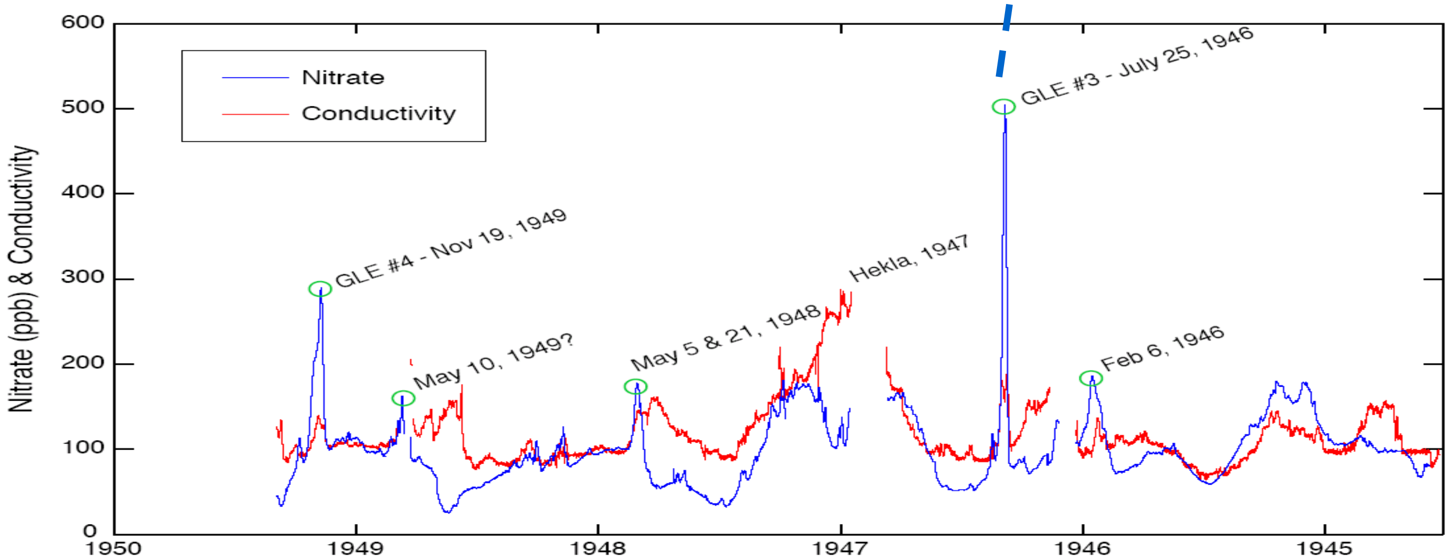
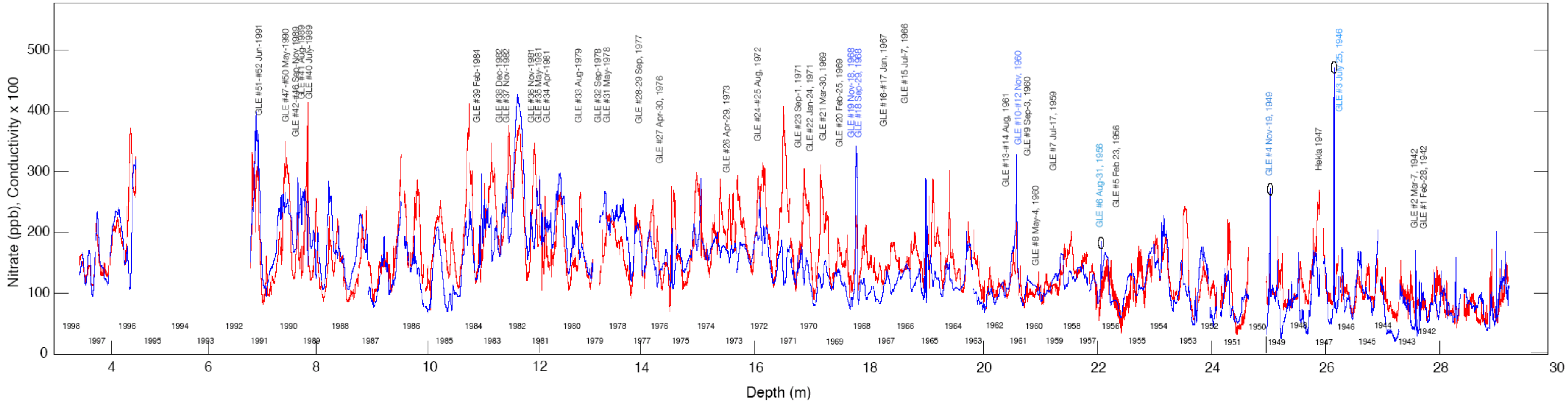


FIG. 1. Three unusual increases in cosmic-ray intensity at Cheltenham Maryland, during solar flares and radio fadeouts.



First 30-meter Cores Analyzed



Next steps:

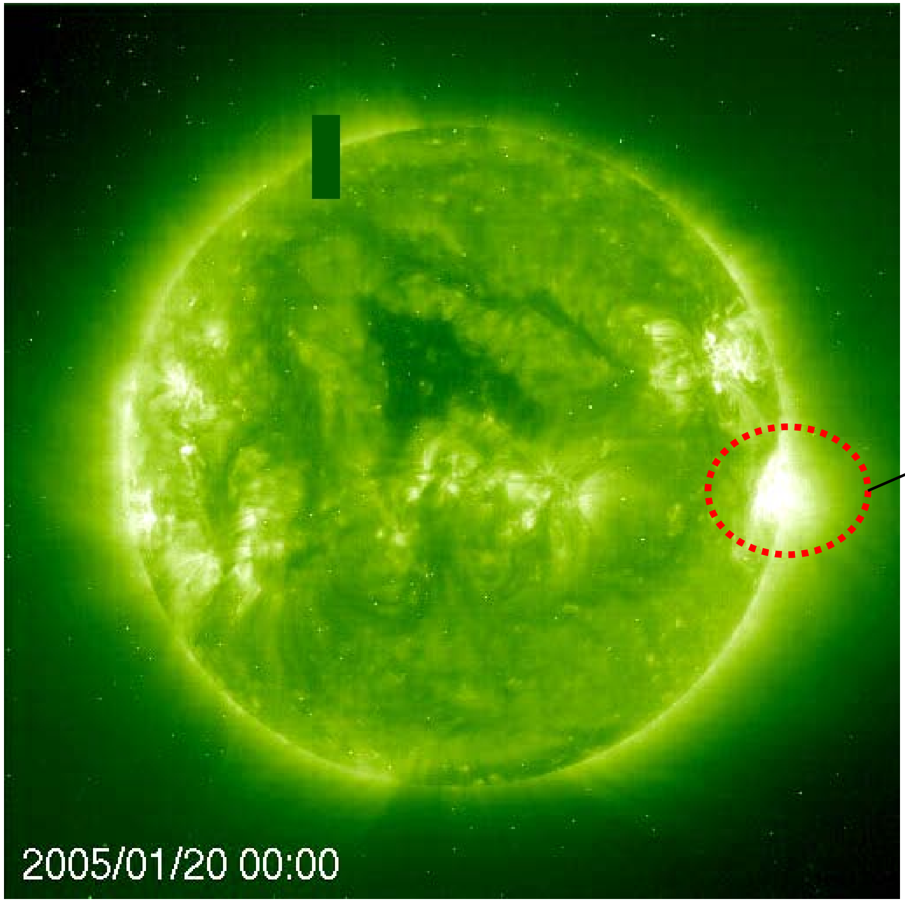
1. Refine stratigraphy/chronology
2. Explore impulsive nitrate events and solar-cycle dependence of background (GCR modulation?)
3. Calibrate nitrate peaks with space-age protons measurements
4. Acquire deeper cores to establish past absolute magnitude and occurrence frequency of solar events going back 100's-1000's of years (More Carrington events anticipated)

So What? Powerful Solar Variability.

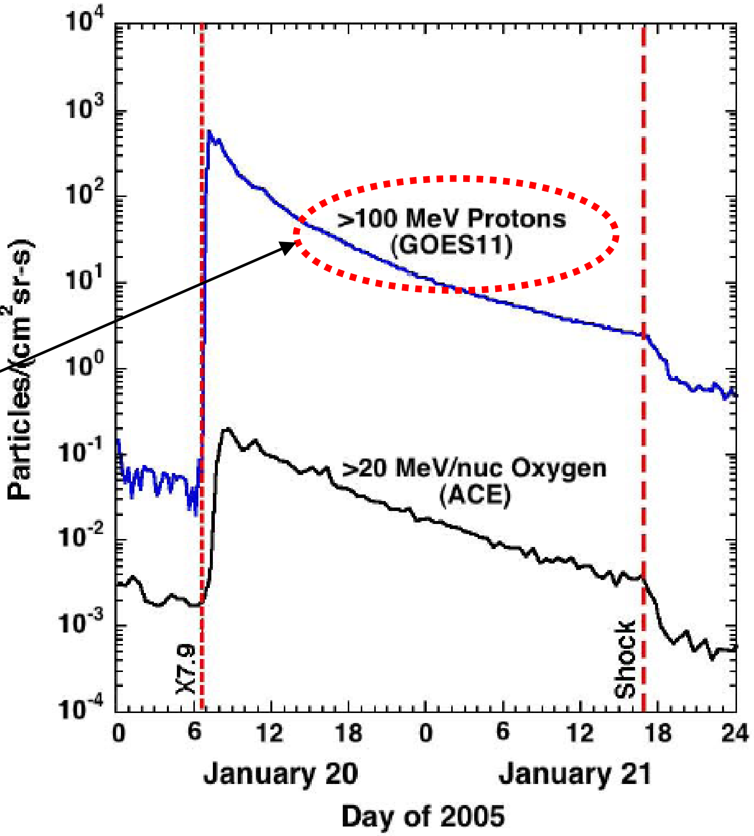
Image credit: J. Koeman

- Near solar minimum
  - Few sunspots
  - Few flares
  - Quiet corona
- Giant sunspot 720
  - Sudden appearance
  - Strong magnetic field
  - Very large
  - On west limb by January 20

Who Cares? Astronauts, s/c Operators



dt < 30 minutes



Magnitude and Scope of Effects?

- ISS: 1 REM (Roentgen Equivalent Man, 1 REM ~ 1 CAT Scan)
  - Scintillations
  - Hardened shelter
- Spacesuit on Moon 50 REM (Radiation sickness)
  - Vomiting
  - Fatigue
  - Low blood cell counts
- 300 REM+ suddenly
  - Fatal for 50% within 60 days
- Also
  - Two communication satellites lost
  - Airplanes diverted from polar regions
  - Satellite tracking problems, degradation in solar panels

How Big is Big? Potentially Fatal.

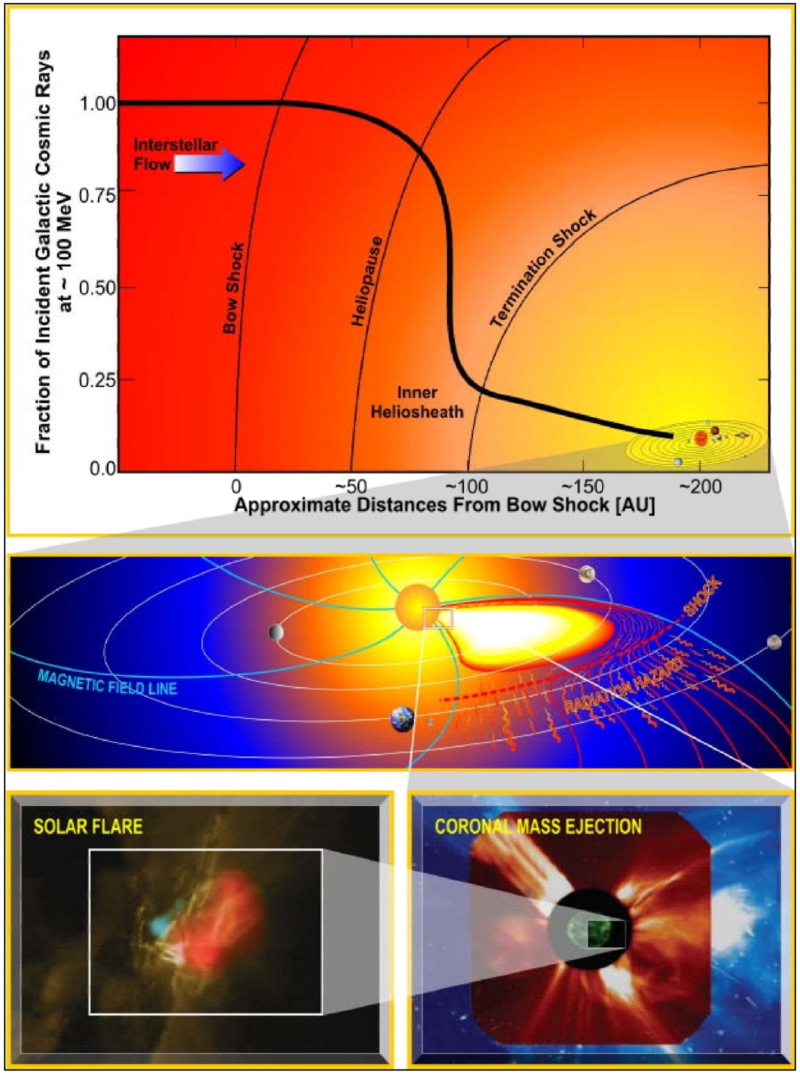
Big Bear Solar Observatory

- Apollo 16 in April 1972
- Flare on August 7, 1972
- Apollo 17 that December
- Derived dosage 400 REM
- Michener's "Space" is based on this event

Summary: Radiation Hazards

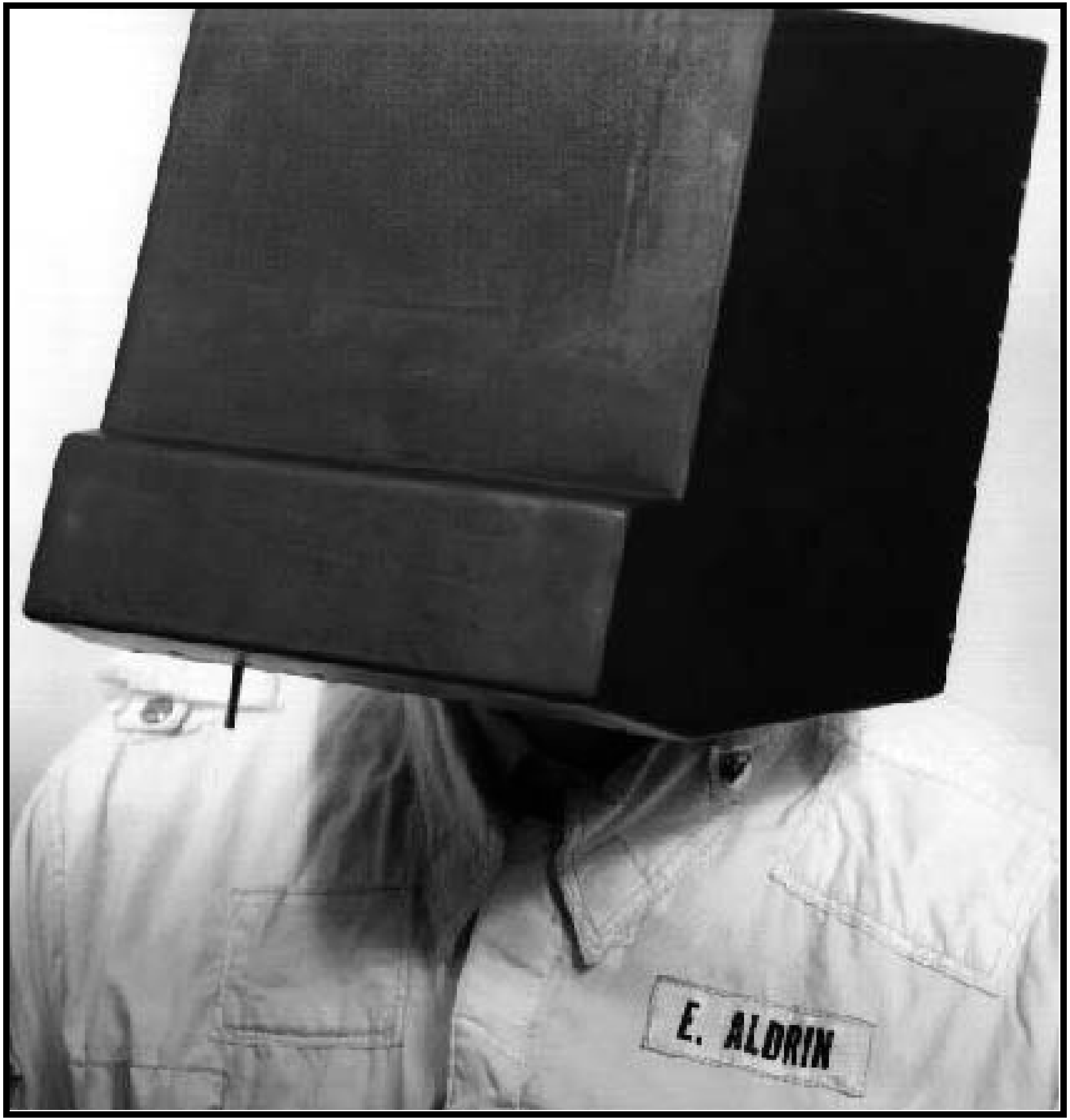
- Galactic Cosmic Rays (GCRs)
  - Steady Background
  - Career limit in ~ 3 years
  - Some predict that 50% of an astronauts DNA would be shattered during a round-trip mission to Mars

- Solar Energetic Particles (SEPs)
  - Acute Sources
  - ESPs versus impulsive component
  - Time-dependent response
  - Difficult to predict



Radiation in Past and Current Spaceflight Operations: Apollo-Era

- Apollo-era cosmic ray detection and human effects experiment
- Buzz Aldrin’s head-gear was used for assessing cosmic ray effects in the human head
- This is what the astronaut did who rode around the Moon in the CM while the others cavorted on the surface



Radiation Measurements for Lunar Operations

Eddie Semones
Space Radiation Analysis Group

Johnson Space Center

Purpose of Radiation Monitoring

- Active radiation monitoring is the primary means for controlling/evaluating crew exposure during missions.
- Provides Flight Control Team insight to radiation environment that could cause acute medical effects that would impact success of mission.
- Provides data for post mission analysis of incurred risk due to crew during mission.
  - Forms database of exposure conditions for risk analysis supporting future missions and crew medical record.

Radiation Monitoring History

- All manned programs have had radiation monitoring hardware
  - Mercury, Gemini, Apollo, Shuttle, ISS

- Typical suite included passive monitoring of crew/area locations and active monitoring with charged particle spectrometers and dosimeters (ion chambers/tissue equivalent proportional counters).

- Improvements have been made in functionality and performance of the types of monitoring, but physics/sensor solutions are similar today.

Apollo Radiation Monitoring (active)

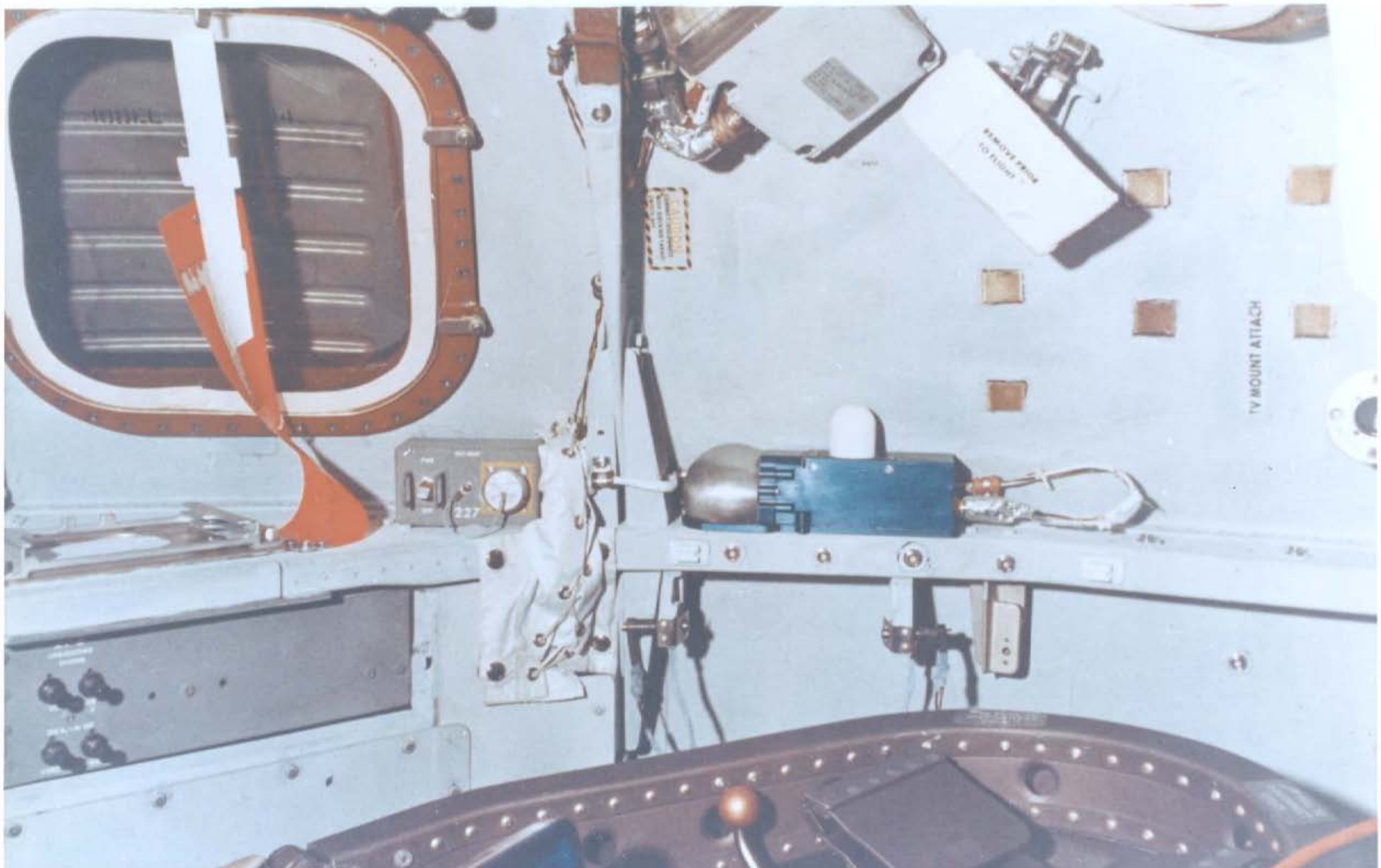
- Nuclear Particle Detection System (NPDS)
  - 5 lbs, 83 in^3
- Van Allen Belt Dosimeter (VABD)
  - 4 lbs, 60 in^3
- Radiation Survey Meter (RSM)
  - 1.5 lbs, 27 in^3
- Personal Radiation Dosimeter
  - 0.44 lbs, 5.4 in^3 (3X)
  - 2 units integrated into area monitor

Total = 11.8 lbs,185 in^3

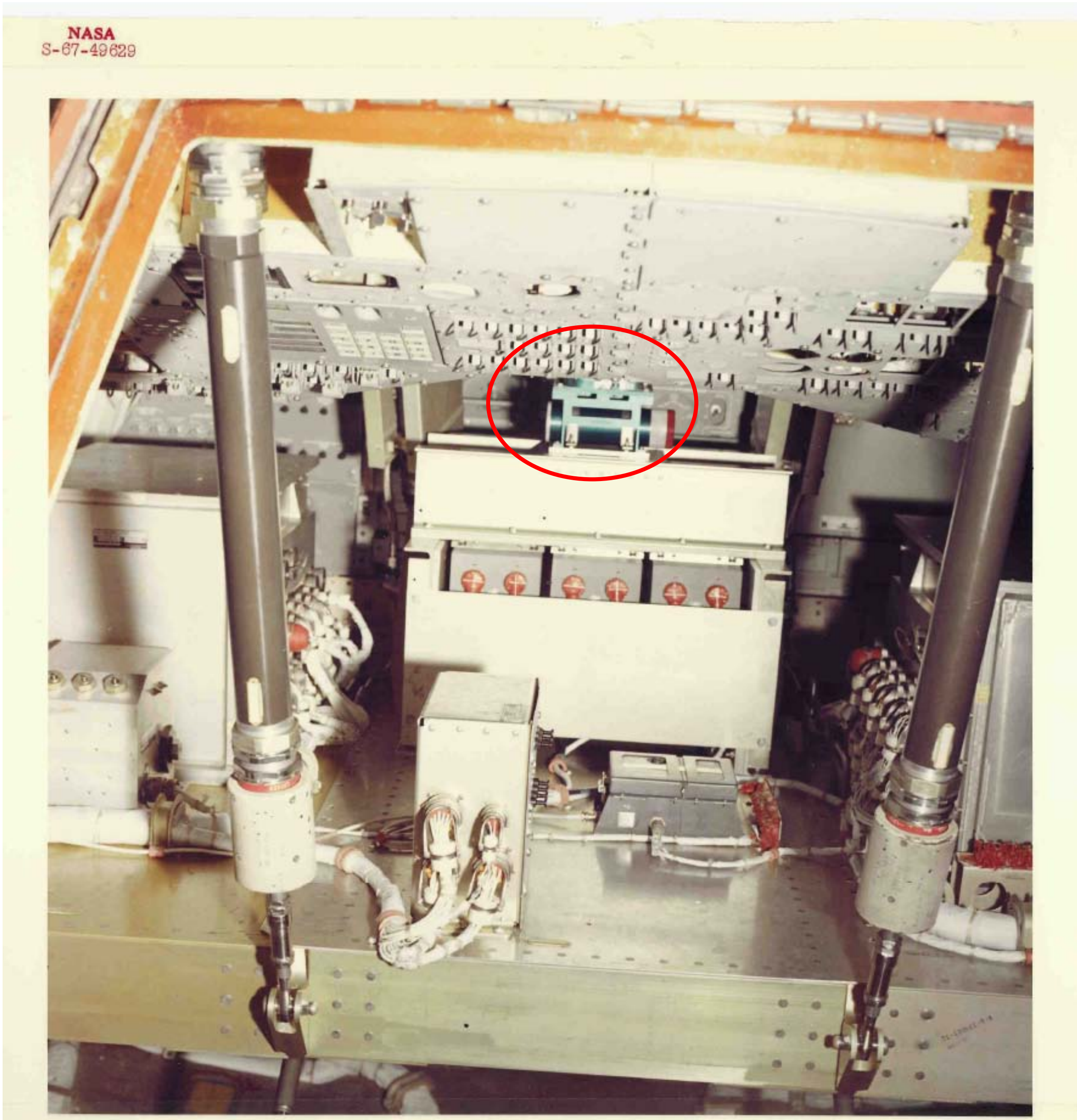
NOTE: Additional passive hardware and flight specific measurements were conducted.

NASA-S-69-455

VAN ALLEN BELT DOSIMETER



Personnel Radiation Dosimeter and Passive Dosimeter Stack



Personal Radiation Dosimeter (Class I)

Radiation in Past and Current Spaceflight Operations: Shuttle/ISS

Radiation Measurement Requirements for Shuttle/ISS

3.2.7.2.4 Absorbed Dose Monitoring

The vehicle shall provide an omnidirectional, portable system that can continuously measure and record the absorbed dose from charged particles with linear energy transfer 0.2 to 1000 keV/micrometer, as a function of time, at a tissue depth of >=2 mm. [HS3089]

3.2.7.2.3 Dose Equivalent Monitoring

The vehicle shall provide an omnidirectional, portable system that can continuously measure and record the dose equivalent from charged particles with linear energy transfer 0.2 to 1000 keV/micrometer, as a function of time, at a tissue depth of >=2 mm. [HS3088]

Both requirements can be met by a single instrument currently are on Shuttle/ISS

Measurement Requirements (continued)

3.2.7.2.1 Charged Particle Monitoring

The vehicle shall continuously measure and record the external fluence of particles of $Z<3$, in the energy range 30 to 300 MeV/nucleon and particles of $3 \leq Z \leq 26$, in the energy range 100 to 400 MeV/nucleon and integral fluence measurement at higher energies, as a function of energy and time, from a monitoring location that ensures an unobstructed free space full-angle field of view 1.1345 Radians (65 degrees) (TBR-006-023) or greater. [HS3086]

Provides different capability than HS3088-3099.
Not redundant.

Radiation and Future Spaceflight Operations: Moon, Mars, and Beyond

ConOps Overview

- **Operational awareness during mission**
  - **Alarming**
  - **Tracking and trending of mission exposure**
  - **Flight rules**

- **Solar particle event alarming and characterization**
  - **High exposure rates in the CEV possible**
  - **Crews most vulnerable to acute effects during lunar phases**

- **Dynamic, unpredictable radiation environment**
  - **No rapid crew return**
  - **Uncertain modeling capability drives need for monitoring**

- **Crew exposure records (post mission)**
  - **Radiation Exposure Histories**
  - **Crew selection – re-flight**
  - **Measurement of primary fields allows for changes in radiation protection philosophy over time**

In-situ radiation monitoring is the main input to operations

CEV ConOps

- Omnidirectional system will be used to provide point measurements of the ambient exposure quantities (absorbed dose/dose equivalent). Flight Rules and Mission limits will be based on these quantities.
  - During quiet conditions the measurement will be made at a fixed location in habitable volume.
  - During solar particle events crew would be survey the habitable volume at various locations to determine lowest dose rate areas.
- Charged Particle Monitor will be used to characterize the primary charged particle radiation environment that can be used to calculate doses at any location within CEV-> human body. Omnidirectional system cannot be used for this purpose.
  - This includes galactic cosmic rays (GCR), trapped belt, and SPE radiation field measurements. This provides a complete record of crew exposure for the duration of the mission.

CEV ConOps

- SPE Monitoring
  - Events can last several days
  - The intensity of the radiation field can change orders of magnitude in periods of time less than 1 hour
  - Ground following/processing of the telemetered data is required to enable analyses utilized in the decision making process
  - Event could occur/continue during sleep periods
    - Decision to wake up crew would be aided by on ground analysis of cyclic data
  - Event could occur during critical phase of mission that would limit crew involvement and would require ground only evaluation
  - Local display/alarm will be available
    - For times when crew is LOS, alarm would allow for autonomous action by crew
- TLI (Trans Lunar Injection)
  - For incomplete TLI burn, CEV could be in orbit that is in an intense region of the trapped radiation belts. High dose rates would be possible
  - Crew would need to survey habitable volume to determine impacts

Characterizing the Deep Space Radiation Environment: Observations

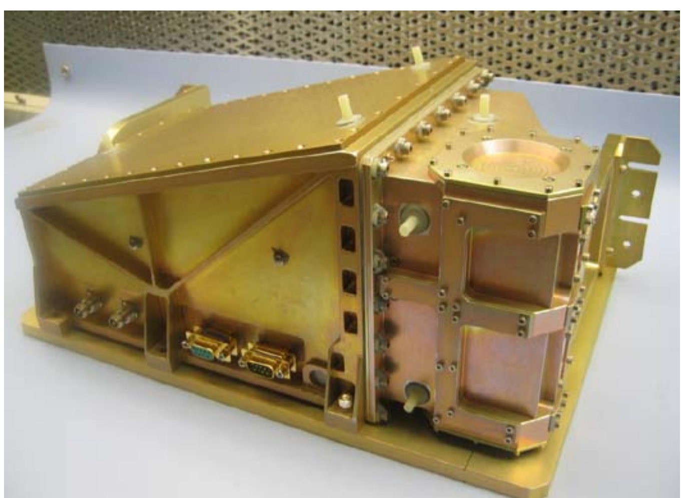
CRaTER Instrument Summary

Cosmic Ray Telescope for the Effects of Radiation (CRaTER) Investigation

(Spence et al., SSR, 2010)

"Luna Ut Nos Animalia Tueri Experiri Possimus"

("In order that we might be able to protect and make trial of living things on the Moon")



ESMD Measurement Goals

To characterize the global lunar radiation environment and its biological impacts

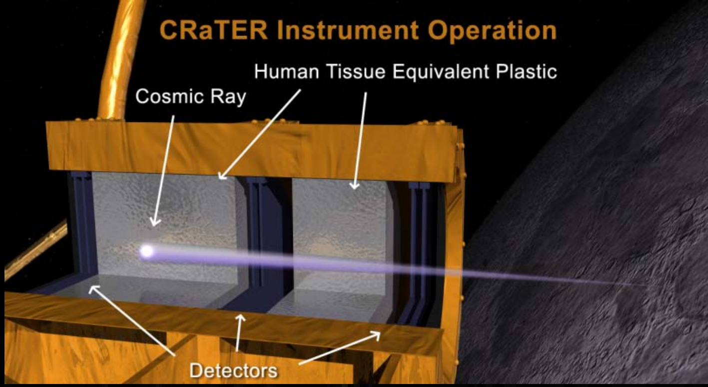
- Six-element, solid-state detector and tissue-equivalent plastic (TEP) telescope

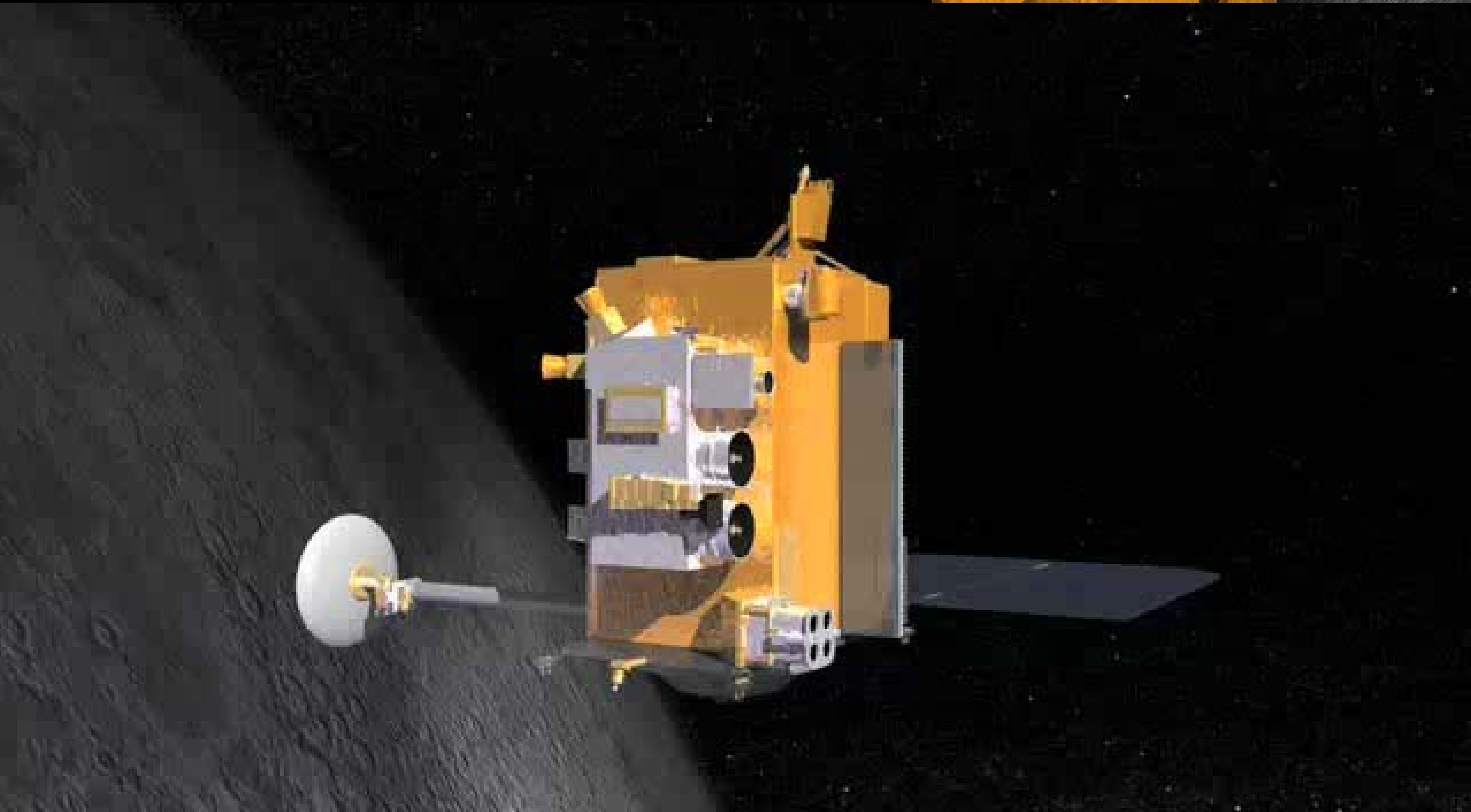
- Sensitive to cosmic ray particles with energies greater than ~10 MeV, primarily protons, but also heavy ions, electrons, and neutrons
    - *Galactic cosmic rays – GCRs*
    - *Solar energetic particles– SEPs*

- Measure spectrum of Linear Energy Transfer (LET = energy per unit path length deposited by cosmic rays as they pass through or stop in matter) behind different amounts of TEP

- Accurate LET spectrum is missing link needed to constrain radiation transport models and radiation biology to aid safe exploration

CRaTER Concept of Operations





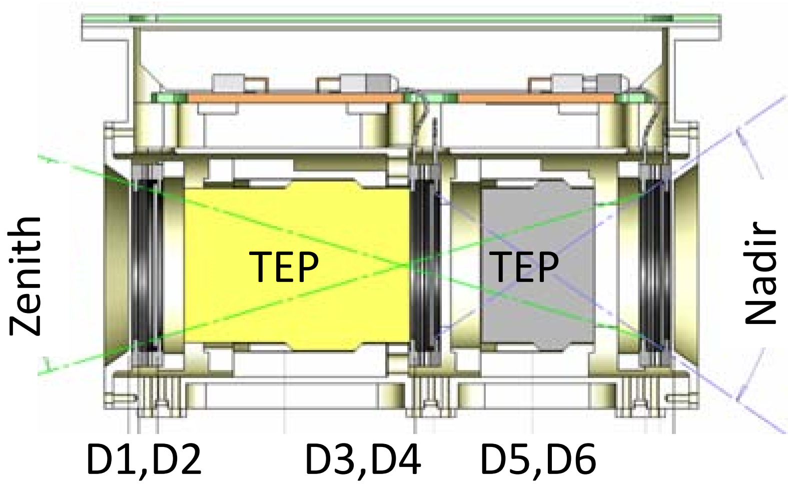
CRaTER Performance Specifications

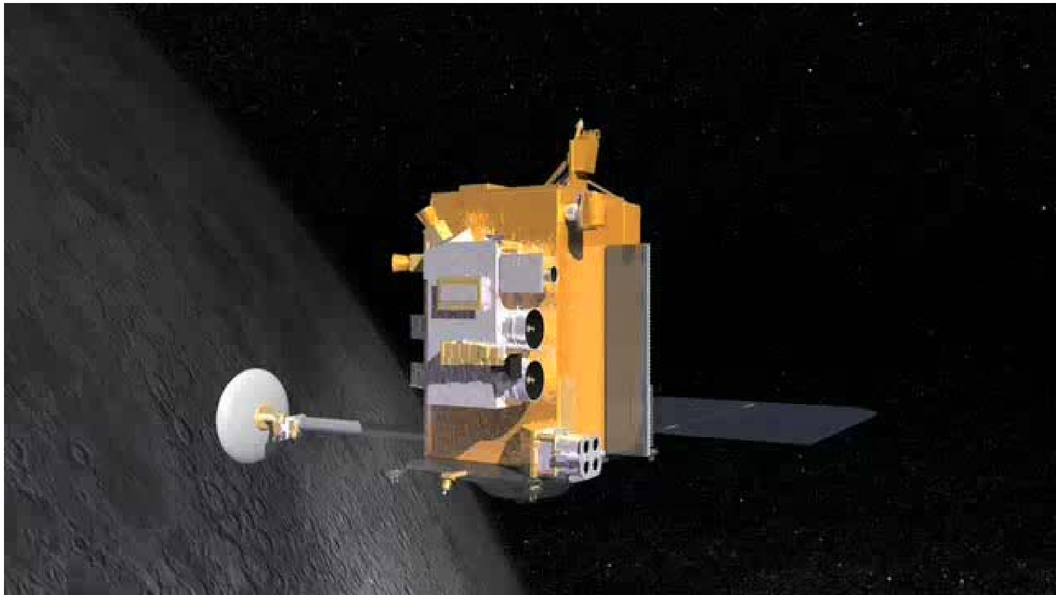
CRaTER's design has thick/thin detector pairs at 3 points through TEP:

- 3 "low LET" thick detectors (D2,D4,D6)- 200 keV to 100 MeV
- 3 "high LET" thin detectors (D1,D3,D5) - 2 MeV to >300 MeV
- **Energy resolution <0.5%** (at max energy); GF ~1 cm^2-sr (typical)

This corresponds to:

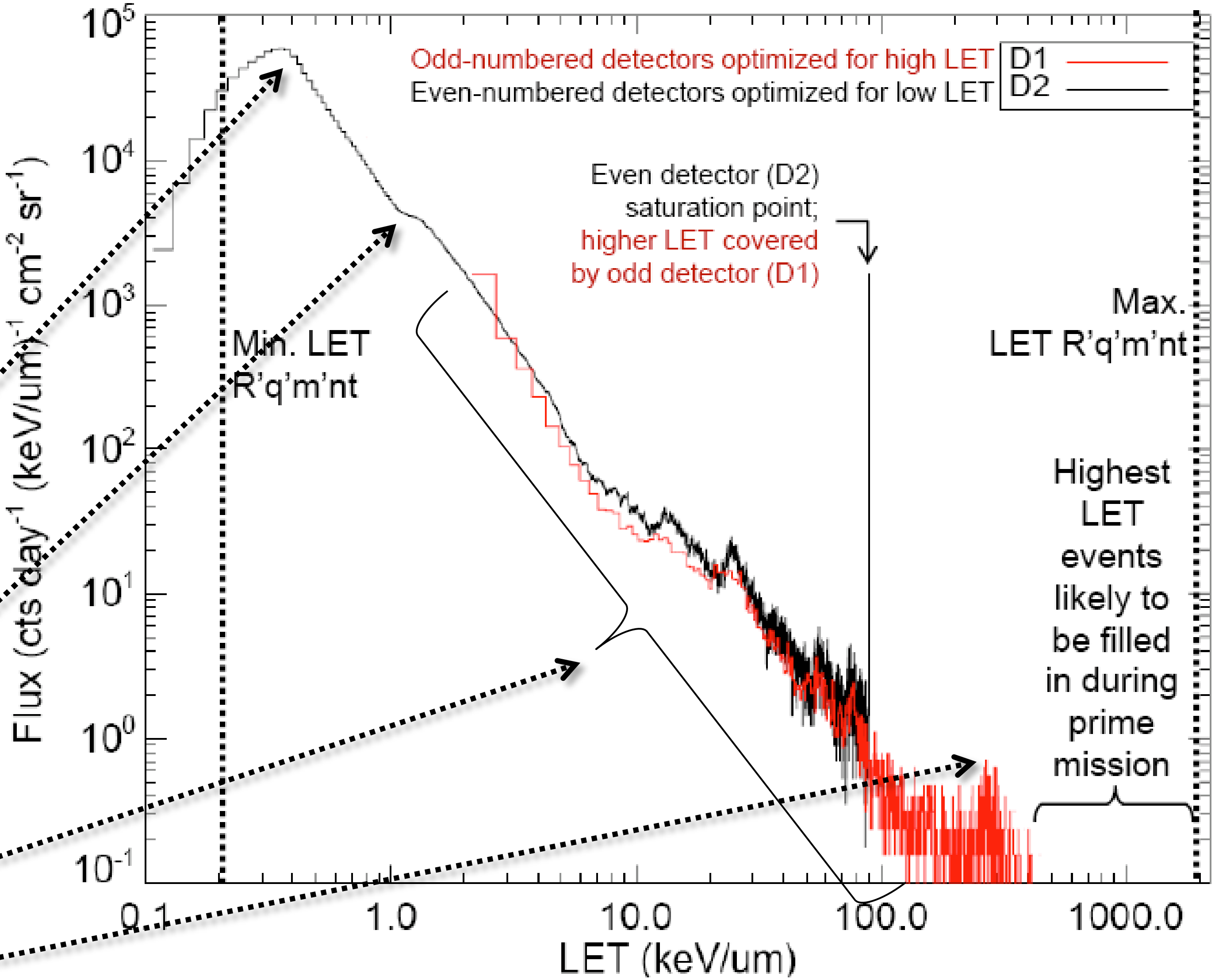
- LET from **0.2 keV/µ to 2 MeV/ µ**
- Excellent spectral overlap in the **100 kev/µ** range (key range for RBEs)
- 100 kbps data rate – telemeter every pulse height in all six detectors whenever any one detector passes its detection threshold (i.e., no inflight coincidence logic required as is typical with most experiments)





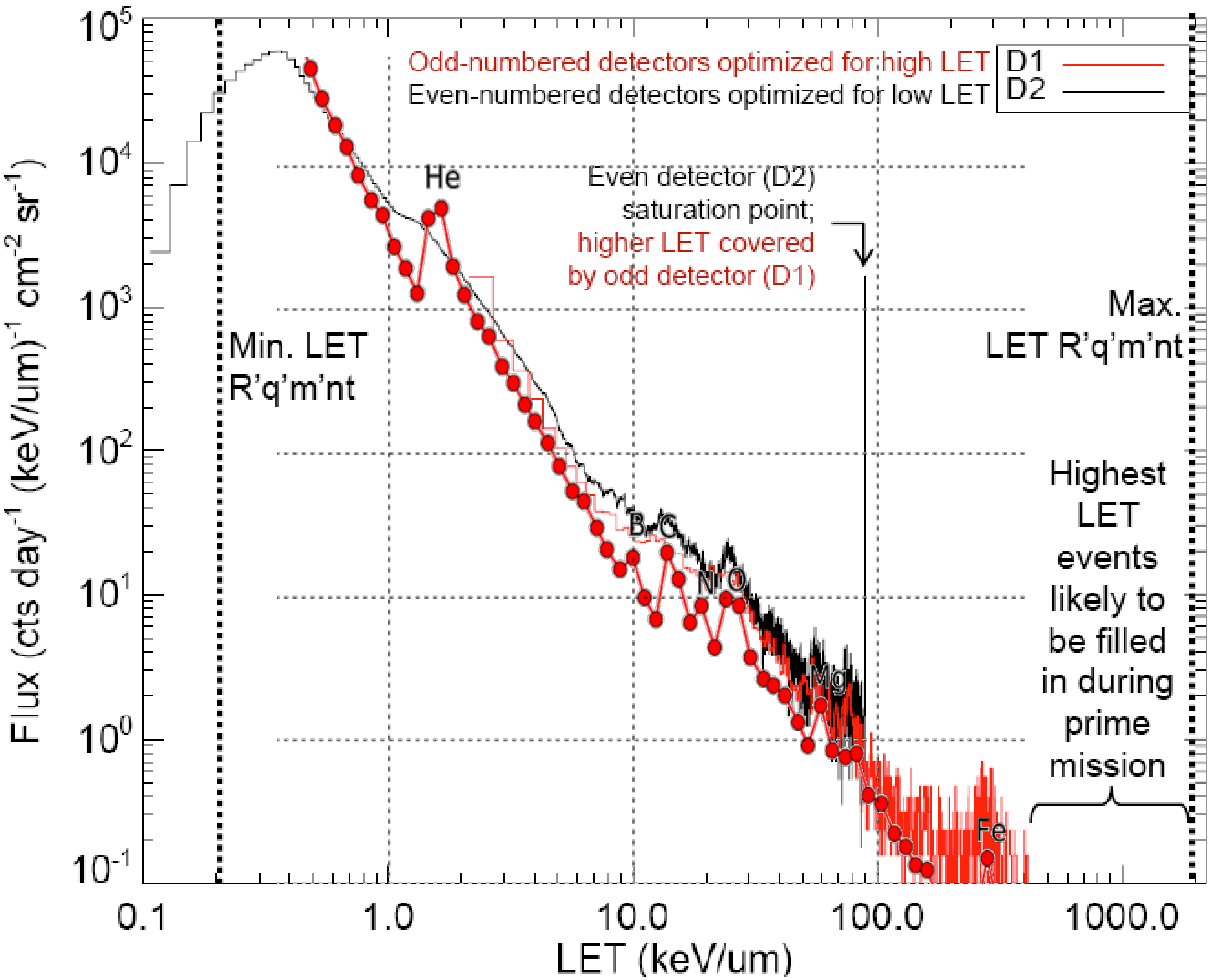
1st-Year Highlight: GCR LET Spectra

- **Composite D1, D2 LET spectra at zenith entrance constructed from 2-4-6 coincident events**
- **Protons contribute most to peak at ~0.4 keV/µm**
- **Helium ions emerge in spectrum at ~1 keV/µm**
- **All heavier ions out to iron peak at ~300 keV/µm**

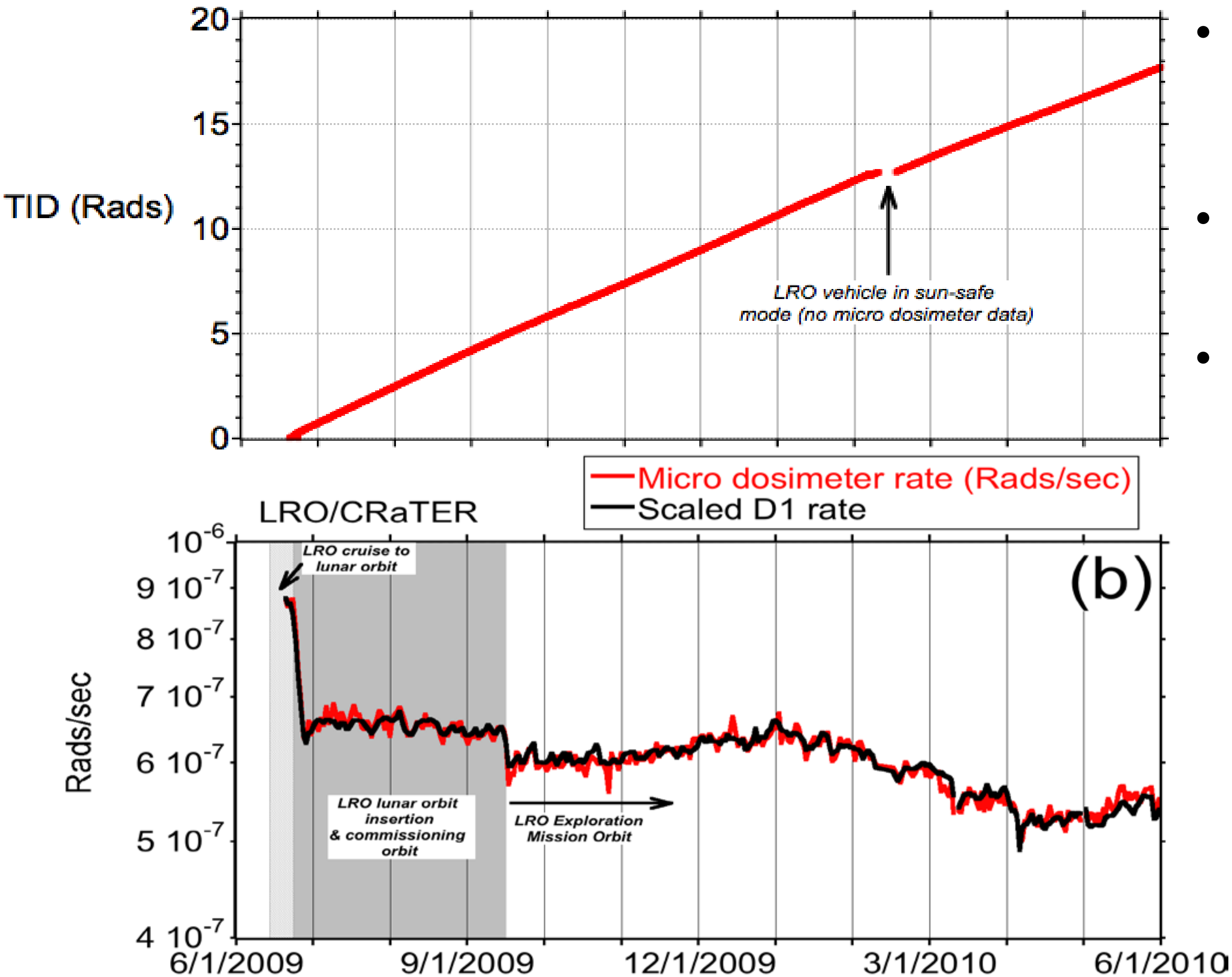


Measured vs. Modeled GCR LET Comparison During Solar Minimum

- Compare CRaTER LET spectrum to comparable model predictions
- Use CREME86 model with GCR flux from prior solar minimum conditions (1996)
- Compute LET in silicon behind 1mm of aluminum (similar thickness to CRaTER's zenith endcap)
- Ion peaks well aligned
- LET flux **higher than last solar cycle**

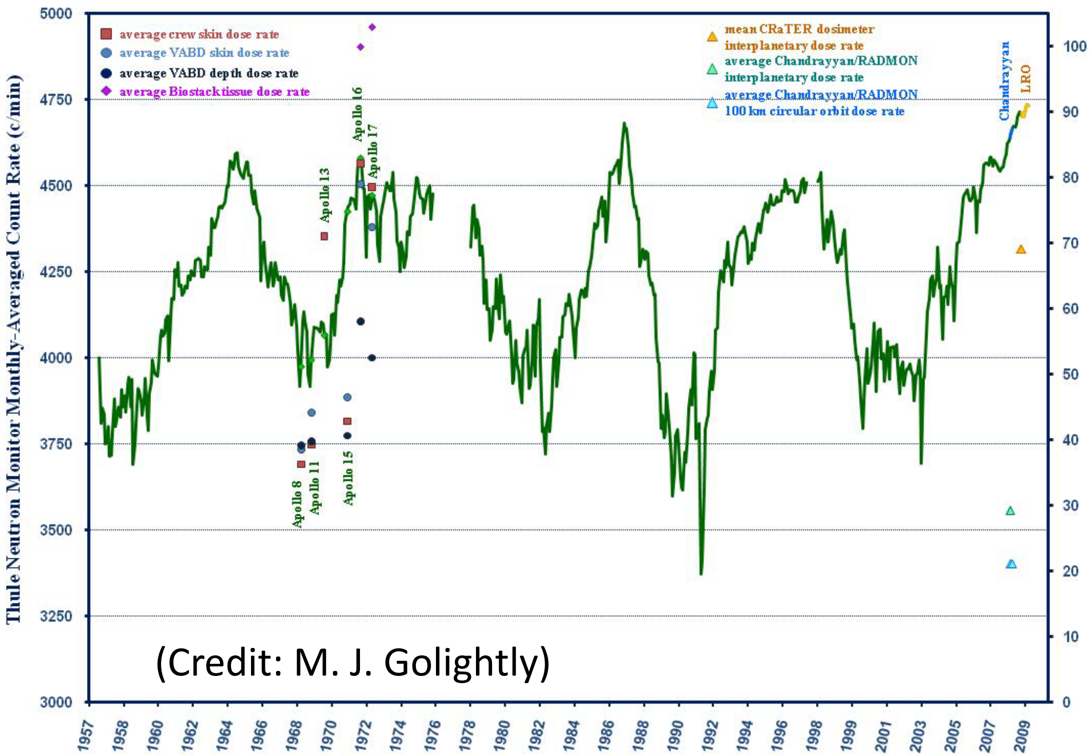


Radiation Dose and Dose Rate During Deep, Prolonged Solar Minimum

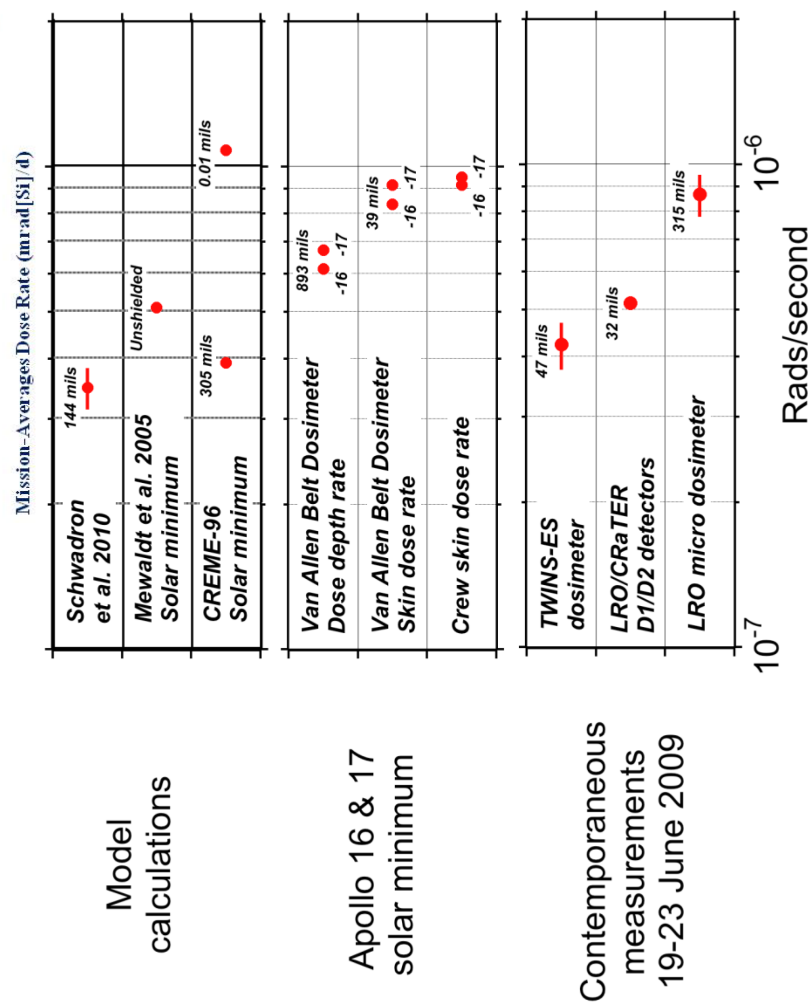


- Total ionizing dose (TID) in silicon for 1-year ESMD mission ~18 rads
- Typical mission dose rate ~0.6 μRads/sec
- Dose rate variations:
  - Highest during cruise phase in deep space
  - Lower during commissioning phase
  - Variations since 9/09 track solar cycle
  - GCR peak in ~Jan 2010; dropping steadily while coming out of solar minimum

Lunar Orbit Dose Rate Comparisons with Apollo-era Estimates

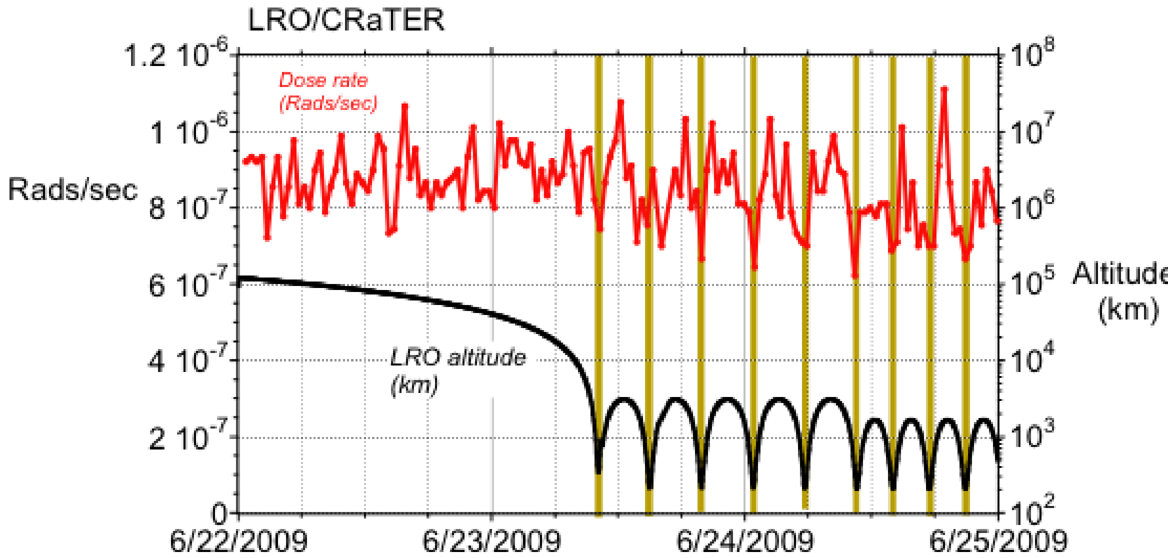


(Credit: J. Mazur)



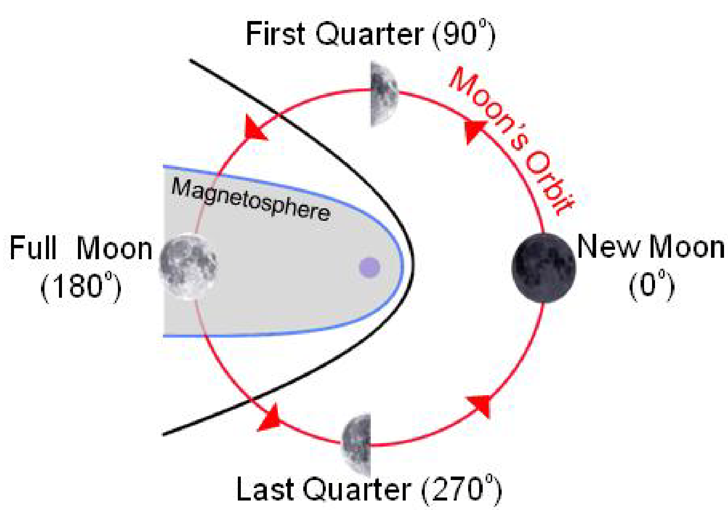
- LRO dose rates compare favorably with Apollo-era estimates, however factor of 3 between contemporaneous measurements, models, and solar cycle differences require reconciliation

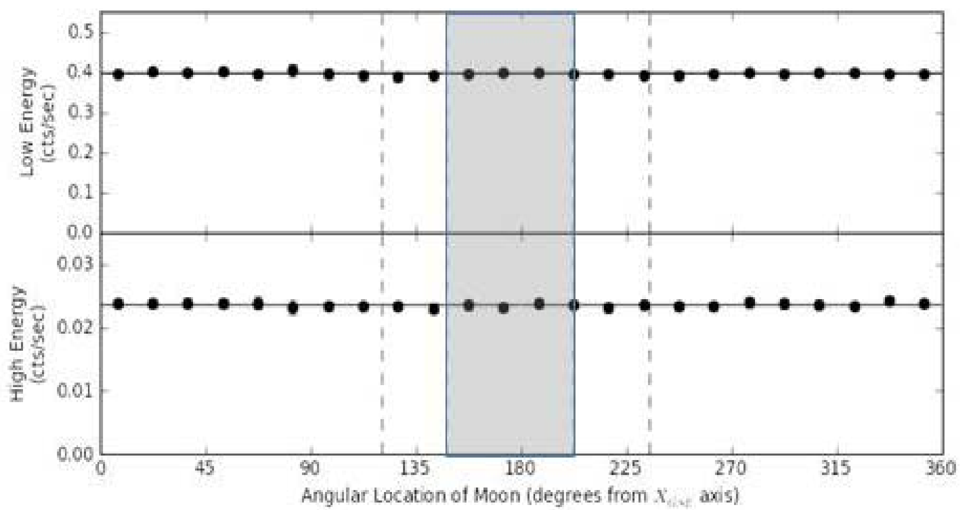
Assessment of Sources of Variability in Galactic Cosmic Rays (GCR) at Moon



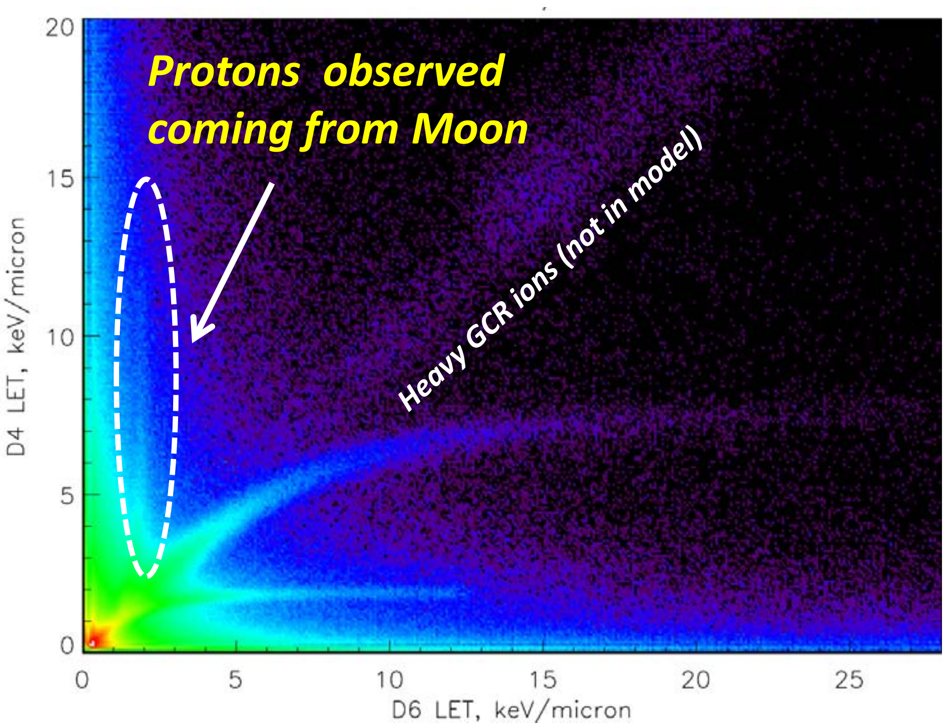
- Altitude dependent dose rate consequence of Moon blocking more or less of the primary GCR (J. Mazur)

- CRaTER confirms that Earth's distant magnetosphere provides no measurable shielding from GCR (T. Case)

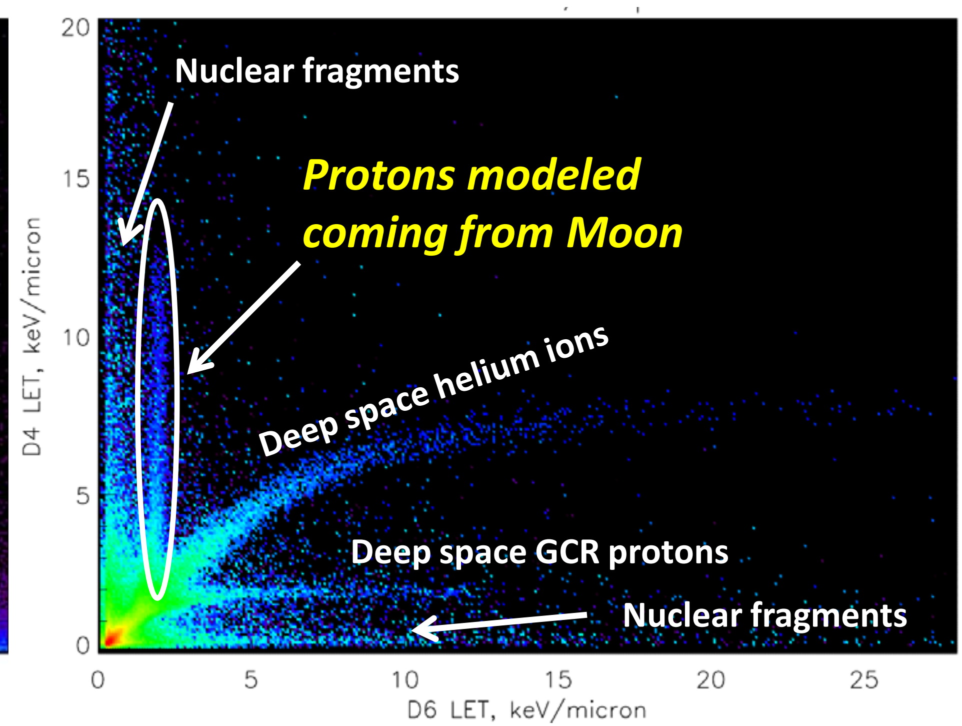




First Direct Measurement of >15 MeV Albedo Protons from Lunar Regolith



CRaTER GCR Observations

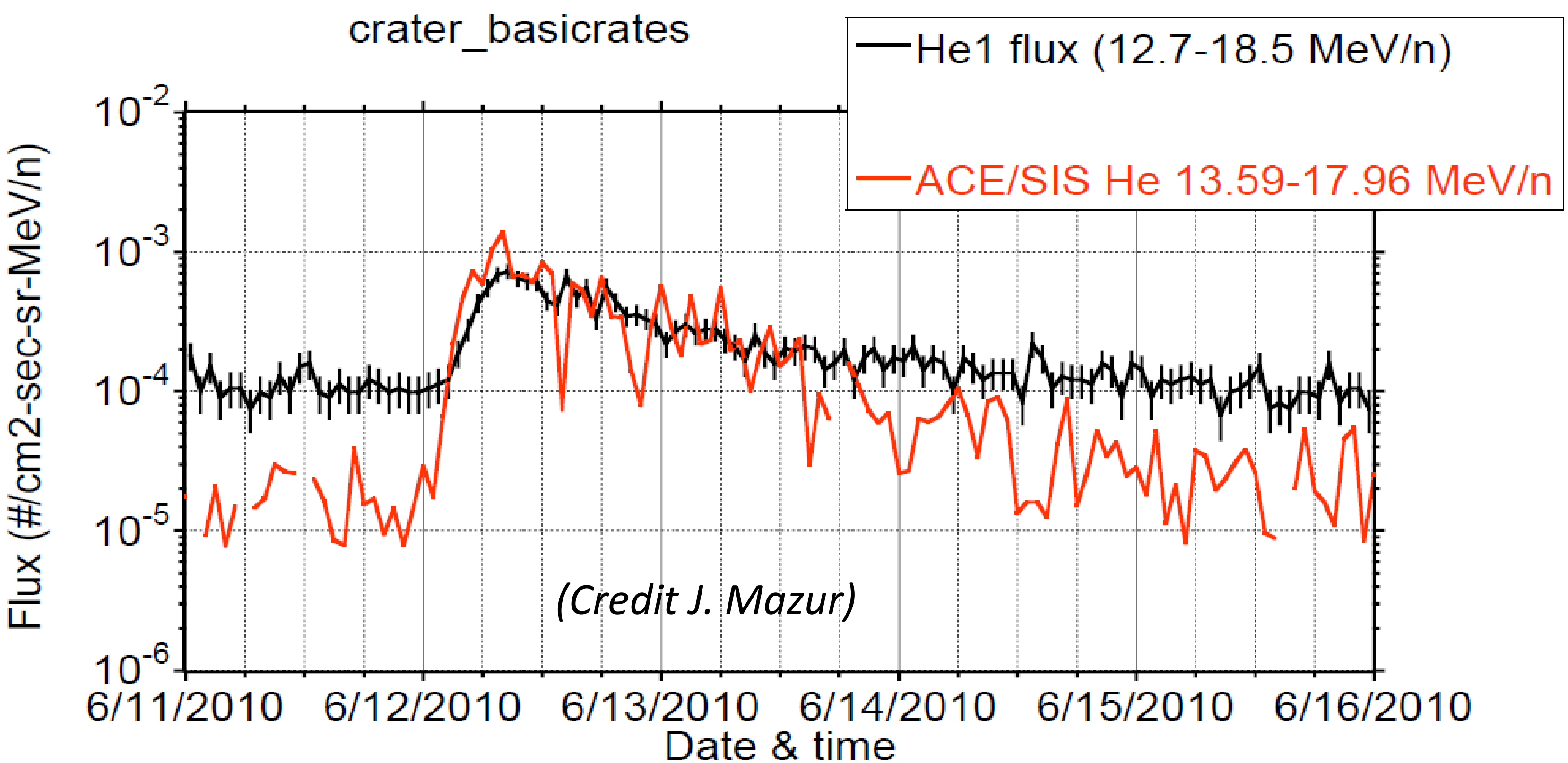


CRaTER Model Response to GCR

- **CRaTER confirms existence of lunar proton albedo (adds to well-known neutron albedo)**
- Upward-moving lunar protons (albedo) created from primary GCR slamming into the Moon
- Nuclear fragments (mostly pions, kaons, etc.) generated as GCR interacts with tissue-equivalent plastic within CRaTER – a major motivation for this experiment!
- Heavy GCR ions (not included in model) seen clearly in observations out to Iron

(Credit M. Looper)

Detection of First, Weak Solar-Related Energetic Particle Event of New Cycle

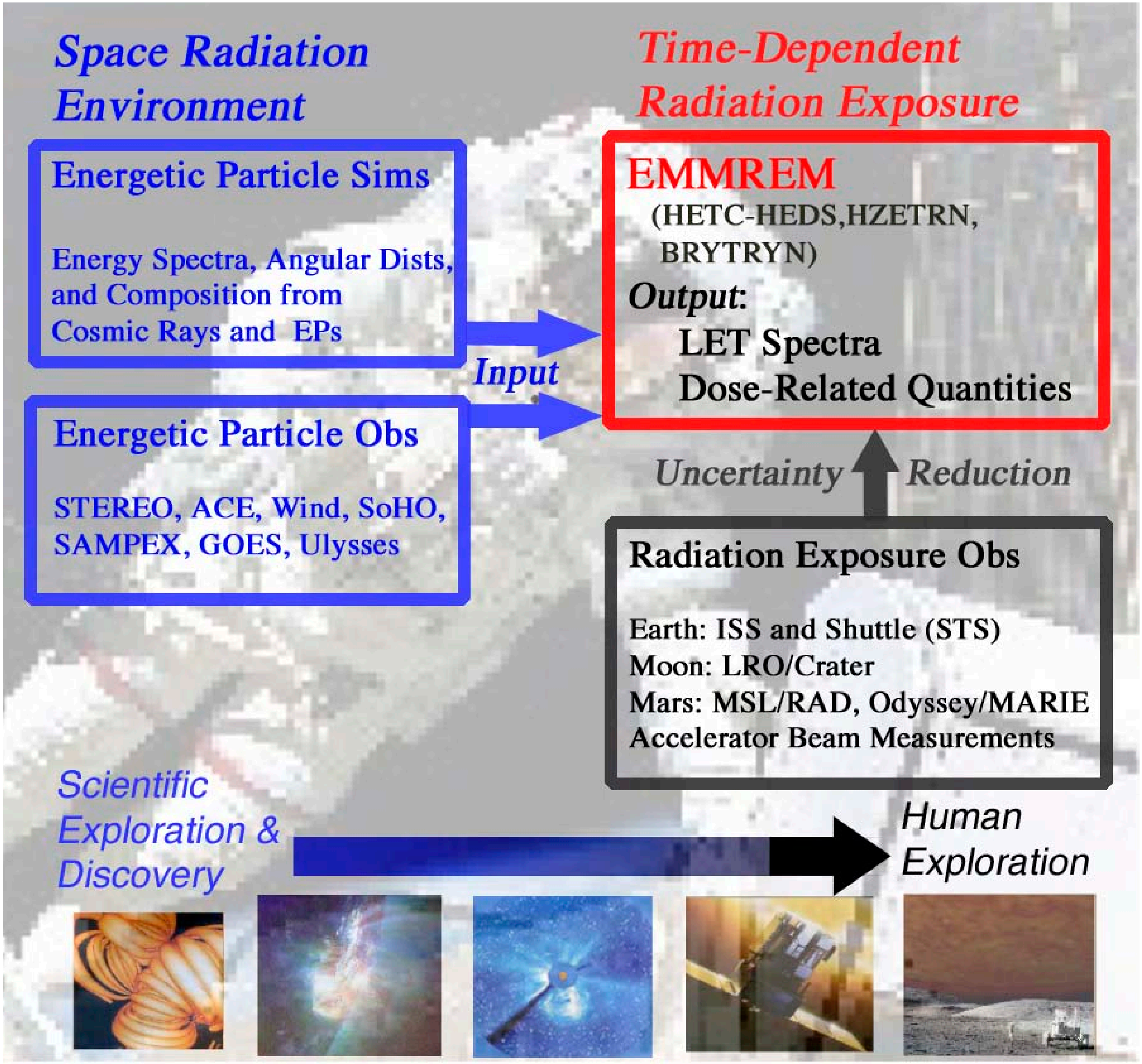


- CRaTER detection of weak event includes alpha particles with high-energy-spectral resolution; comparison with ACE observations underway and favorable

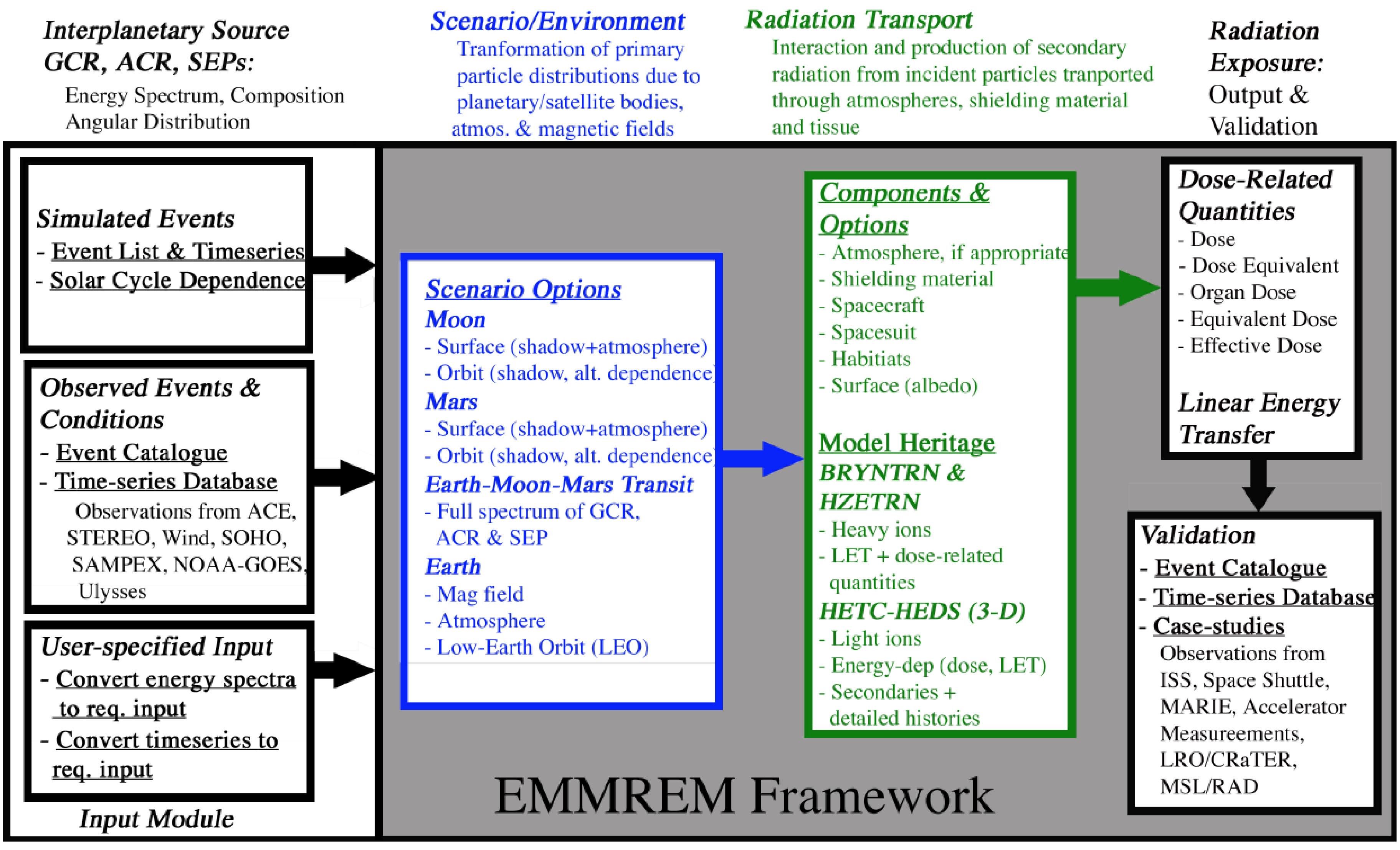
- Strong detection by CRaTER despite unremarkable event promises greater science opportunities as Sun wakes up…

Characterizing the Radiation Environment: Forecasting

One example:
EMM-REM
(Earth Moon Mars Radiation Environment Module;
Nathan Schwadron, PI)


Space Radiation Environment
Time-Dependent Radiation Exposure
Energetic Particle Sims
Energy Spectra, Angular Dists, and Composition from Cosmic Rays and EPs
EMMREM
(HETC-HEDS,HZETRN, BRYTRYN)
Output:
LET Spectra
Dose-Related Quantities
Input
Energetic Particle Obs
STEREO, ACE, Wind, SoHO, SAMPEX, GOES, Ulysses
Uncertainty
Reduction
Radiation Exposure Obs
Earth: ISS and Shuttle (STS)
Moon: LRO/Crater
Mars: MSL/RAD, Odyssey/MARIE
Accelerator Beam Measurements
Scientific Exploration & Discovery
Human Exploration

EMM-REM Framework



Review: The Space Radiation Environment

Solar particle events (SPE) (generally associated with Coronal Mass Ejections from the Sun):

- medium to high energy protons
- largest doses occur during maximum solar activity
- not currently predictable
- MAIN PROBLEM: develop realistic forecasting and warning strategies

Trapped Radiation:

- medium energy protons and electrons
- effectively mitigated by shielding
- mainl
- MAIN

Galactic Cosmic Rays (GCR)

- high energy protons
- **highly charged, energetic atomic nuclei**
- not effectively shielded (break up into lig
- abundances and energies quite well kno
- MAIN PROBLEM: biological effects poorl
- significant long-term space radiation haz