ESS 7
Lectures 22 and 23
May 28 and June 2, 2010
Humans in Space
Even if not soon to the Moon or Mars, humans will still be in Space (ISS)
Radiation Doses and Risks

• When high energy particles encounter atoms or molecules within the human body, ionization may occur.
  – Ionization can occur when the particle is stopped by an atom or molecule. The resulting radiation can ionize nearby atoms or molecules.
  – Bremstrahlung (radiation released by a “near” miss) can also ionize atoms or molecules.

• A rad is the amount of ionizing radiation corresponding to 0.01 Joule absorbed by one kilogram of material.
  – The rad unit is independent of the type of radiation.
  – ~100 rads will cause radiation sickness (1 Gray (Gy) = 100 rads).
  – 1 Gy has a high probability of killing a cell by producing a lesion in its DNA.
  – 1 rad received from x-rays is less harmful than 1 rad from high energy protons.
Radiation Damages DNA

Indirect Route

Radiation → Water → Free Radical → Damage

Direct Route

Radiation → Damage
Radiation Doses and Risks

• The relative biological effectiveness (RBE) of radiation is normalized to 200 keV x-rays.
  – The biological damage is measured in rem (rem=dose(rad)×RBE).
  – The SI unit of equivalent dose is the Sievert – rem=0.01Sv = 1cSv.
  – Electrons, protons, neutrons and alpha particles are the most damaging because they penetrate deeply into human tissue.
  – 1cSv is three years dose on the surface of the Earth.
  – A chest x-ray gives 0.01cSV and a CAT scan gives 4cSV.
  – Values are frequently given as the dose behind 1 gm cm\(^{-2}\) which is roughly the protection of a thick space suit.
  – Current limits for astronauts are 0.5Sv per year – 3% excess cancer mortality risk.
Average Annual Radiation Dose for Average U. S. Citizen

0.35 Rem/y
Sources of Human Risk and Protection

• Astronauts must worry about a number of sources.
  – Galactic cosmic rays
  – Secondary neutrons from heavy galactic ions
  – Solar energetic particle events (SEPs)
  – Relativistic electron events (REE)
  – Passages through the south Atlantic anomaly
  – Radiation belts

• Protection
  – Material thickness based on mass
  – Since in an incoming “beam”, mass/area -> g/cm²
  – A thin layer of lead is like a thick layer of aluminum
  – Having a lot of mass is undesirable in a space application
Shielding – On Earth, usually lead

Radshield.com (not made of lead)
Galactic Cosmic Rays

- GCRs are atomic nuclei – 85% protons, 14% alpha particles and 1% heavy nuclei.
- At solar minimum the dose behind 1gm cm\(^{-2}\) 50cSv/yr
- At solar maximum 18cSv/yr
- Doses <20cSv/yr pose no acute health hazard.
- On a 600 day trip to Mars at solar minimum would use up the lifetime dose of a male and twice the dose of a female (30cSv for men and 15cSv for women).
- A trip to Pluto would essentially kill all of the cells in the body.
A New Record!

Cosmic Ray Fe Nuclei
(270 - 450 MeV/nucleon)

Previous space age record high

Projected from 1951-2005 neutron monitor data and 10.5-yr solar cycle
Solar Energetic Particles (SEPs)

- There are two types of SEP events
  - Impulsive and gradual
  - Fluxes of energetic ions are much higher and longer lived in gradual events. They pose a health hazard.
  - Gradual SEPs are associated with the shock front ahead of CMEs. (>60MeV black, >10MeV mauve, >4MeV blue, >2MEV orange, >1MeV red) The shock is marked with orange bar.
Effects of SEPs

- SEP events during Apollo era
- Flux of >60MeV ions and skin dose.
- Color bars give estimates of the seriousness of radiation.
- If astronauts had been at the moon during the August 1972 storms the dose would have been fatal.
**GCRs and SEPs**

- SEPS and GCRs tend to be anticorrelated.
- The CMEs that create SEPs also cause decreases in cosmic rays called Forbush decreases.
- CIRs do not create SEPs at Earth but have steepened enough by Mars orbit to create SEPs.

![Graph showing neutron monitor and >60MeV SEPs over years](image)
How Dangerous are SEPs?

• Fraction of time since 1968 that daily mean flux (>60MeV protons) exceeds horizontal value.

• Since daily values they are for a 1 day mission.
Probability of encountering SEP versus days beyond the Earth

- Based on “space age” statistics
- Probability of exceeding annual safety limit is ~100%
- Probability of at least one fatal (10cSv) is 10%
- Probability of a 2cSv event (35% fatality rate) is 30%
How much shielding do you need?

- (top) >60MeV flux from SEPs during the August 1972 storm
- (bottom) cumulative skin dose behind various shields.
- Even with 250 gm cm⁻² astronauts would exceed make lifetime limit.
Historic SEP Events

• (top) Frequency of SEP events in number per solar cycle.
• (bottom) >30MeV fluence based on nitrate abundance in ice cores.
• Nitrates are formed by ionization by SEPs and precipitated in snow.
• We are currently in a period with relatively few SEP events.
• In 440 years there were 32 events that would have exceeded the fatal skin dose (10Sv) in near-Earth space (one every 13.75 years).
Is it Possible to Shield a Spacecraft from SEPs?

- The greatest risks are outside of the magnetosphere.
- Is a mini-magnetosphere a possible way to protect astronauts?
- How strong would B have to be?


Building a Mini-magnetosphere in the lab

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Space</th>
<th>Lab</th>
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<tr>
<td>$B_{SW}$</td>
<td>10nT</td>
<td>0.01T</td>
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<tr>
<td>$B_{mag}$</td>
<td>0.1T</td>
<td>0.5T</td>
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<tr>
<td>$n_{sw}$</td>
<td>5 cm$^{-3}$</td>
<td>$10^{12}$ cm$^{-3}$</td>
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<tr>
<td>$V_{sw}$</td>
<td>450km/s</td>
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<tr>
<td>$T_{sw}$</td>
<td>20eV</td>
<td>5eV</td>
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<td>$M_{CA}$</td>
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<td>$M_{cs}$</td>
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<td>$\beta$</td>
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<td>$r_L$</td>
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</tr>
<tr>
<td>$c/\omega_{pi}$</td>
<td>102km</td>
<td>22.8cm</td>
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Can Laboratory Mini-magnetosphere be Scaled to Spacecraft size?

- MHD theory
  - Pressure balance at the magnetopause \( \left[ p + B^2 / 2\mu_0 \right] = 0 \)
  - \( r_{mp} = \left( \frac{KB^2}{2nm_i v^2} \right)^{1/6} \) where B is the magnetic field intensity, n is the density, v is the flow velocity of the solar wind
  - K is a free parameter that accounts for deviation of B from its dipolar value and deviation from specular reflection at the magnetopause (\( p_{dyn} = \kappa nm_i v^2 \)).
How Good is the Simple Model?

- It isn’t clear that the MHD model is good since the Larmor radius of energetic ions is comparable to the mini-magnetosphere.

- Used a very sophisticated “hybrid simulation” to model the lab results and test the MHD model.
Comparison with MHD Model

- MHD model is the solid line.
- Symbols give the results from the simulation.
- B versus distance.
- Excellent agreement at low B.
- At B=0.2T the simulation gave $r_{mp} = 26.7 \pm 2.5$ mm compared with experiment $r_{mp} = 28.5$ mm.
- The MHD works well.
Simulation and MHD plasma values

- For density $r_{mp} \sim n^{-1/6}$
- For velocity $r_{mp} \sim v^{-1/3}$ means larger changes occur for velocity changes.
- For a magnetic field as large as the present simulation, the MHD results say the magnetic field should stand off the solar wind at a distance of $(n/n_{sw})^{1/6} \sim 76$. The stand off distance would be a few meters.
Stopping a 1MeV Proton

- While our magnetic field could stand off the solar wind it would take more to stop a 1MeV proton.
- Plasma injection can change the fall off to $1/r^n$ with $\eta<3$.
- Assume the shielding field can be made to fall off as $1/r$.
- For efficient deflection we need the Larmor radius to be about $1/5$ the distance to the spacecraft.
- A magnetic field of 0.72T would be required.
- This could be accomplished with a 1m current loop and a magnetic moment $M\sim 7.2\times 10^6$ Am$^2$.

*Recall Earth field is 60 $\mu$T - this is a huge field and a huge current!*
Forecasting Space Weather

• Like with terrestrial weather some problems could be lessoned by having accurate space weather forecasts.

• Astronauts on the moon could be placed in protective shelters, astronauts on the space station could be brought back to Earth (with 2 days warning).

• Terrestrial weather forecasters use a combination of data from a large array of observatories and models to create forecasts – data assimilation.

• In space weather there are very few observations between the Earth and Sun so forecasters have turned to theoretical models.

• Most studies use observations from the L1 Lagrange point (~ 230R_E from the Earth). This gives at most 1 hour warning.
An Example of a Space Weather Forecast Model

• The students of ESS 261 studied space weather forecasting and carried out a test of a space weather model (Cartwright et al., 2008).

• There are three main parts of a space weather forecast model
  – A model of CME (or CIR) generation.
  – A model of the transport of CME (or CIR) material through the heliosphere.
  – A model of the interaction of the heliospheric model with the Earth.
A Coronal Mass Ejection Model

• Models of theoretical models of coronal mass ejections have the largest uncertainty.
• Purely theoretical models require extremely large amounts to computer time and there is no agreement on what makes a prominence turn into a CME.
• The ESS 261 students decided to use an empirical approach. They used white light images of a CME to build an empirical model.
  – This is called a cone model.
  – They are limited by two dimensionality of solar coronal observations.
White Light Coronagraph Image of CME

- This image shows the halo CME used in the test.

- A series of images plus surface magnetograms were used as input a model of the solar wind.
Propagation from the Sun to the Earth

- The ENLIL MHD model was used.
- This plot shows the radial velocity of the ICME.
- In the forecast model the CME strikes the Earth (black dot) a glancing blow.
Comparison of ENLIL Simulation and ACE Observations at L1.

- Theoretical CME
  - arrives 14 hours early – results have been shifted.
  - does not reproduce the magnetic cloud.
  - give too large velocity and temperature
Comparison of Magnetosphere for Simulations Based on CME model and ACE data
CME Model Driven Simulation and ACE Driven Simulation Gave Different Results

- CME driven magnetic storm was much less active than that driven by data from the L1 monitor.
- Multiple substorm like signatures in the ACE driven model and only one in the CME model driven model.
- ACE driven model gave ring current consistent with observations while CME model gave a much weaker ring current.
Summary of Space Weather Prediction

• We have some predictive ability, some of this was discussed before (27 day patterns)

• Inputs are needed – Sun, Interplanetary spacecraft

• Most important monitors, ACE, is only 1 hour ahead in the solar wind

• Theory models are good but not great