NEXT GENERATION IONIZING RADIATION CHARACTERIZATION FROM AVIATION ALTITUDE TO DEEP SPACE

Lika Guhathakurta
Concept Developed at NASA Ames Research Center,
Exploration Technology Directorate
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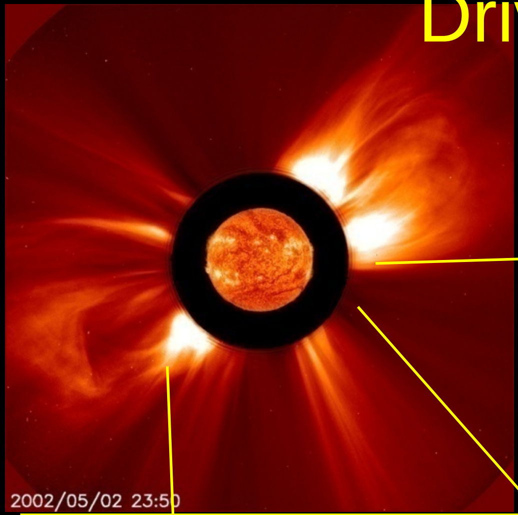
NASA held a Space Radiation Workshop in early November, 2017, with the stated purpose of exploring ways to enable data-rich characterization, forecasting and monitoring of space radiation environments relevant to NASA science, aviation, and deep space exploration. The discussions about galactic cosmic rays, solar particle events, and solar event prediction are all highly relevant to the sustained deep space operations and flights, as well as useful closer to home on aviation and space tourism very much in support of the new space policy directive.

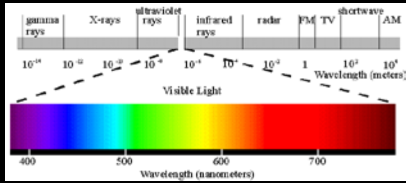
https://www.nasa.gov/ames/partnerships/spaceportal/radiationworkshop

Drivers of Space Weather



Blame it on *Magnetic Field)*

Electro-magnetic Radiation



Ultra Violet and X-ray Radiation

8 minutes

R-Scale

Satellite drag; radio blackouts

Matter

Charged Particle Radiations

10-30 minutes

S-Scale

NOAA Space Weather Scales

Matter

Magnetic Fields

Radiation: astronaut health. aviation & satellite function

Magnetized Blobs of Solar Material

18-96 hours

G-Scale

Aurora; geomagnetic storms & radio disturbances

“Space Weather” vs. “Radiation”

There is a potential for confusion between the terms “space weather” and “radiation” in a study of operational requirements

Space weather is the broader term and encompasses a wide range of phenomenology with operational impact

The dominant subset of space weather impact is related to the radiation, or energetic particle, environment, including electrons, protons, neutrons, and charged ions with energies from KeV to GeV

The radiation environment inside a spacecraft or habitat is modified by the surroundings (shielding, atmosphere, tissue, etc) and can be enhanced by human-induced radiation sources (power supplies, medical monitoring, invasive radioisotopic tracers)

Scope of Space Weather Impact

Human Space Flight

- Radiation exposure increases risk to long term astronaut health, some risk of acute effects
- Radiation event can damage/disrupt critical electronics or interfere with communications
- Response to radiation event can temporarily suspend mission operations and/or be mission limiting

Robotic Missions

- Radiation exposure limits life of some electronics and components
- Radiation event can damage/disrupt electronics or interfere with communications
- Response to radiation event can temporarily suspend mission operations

Launch Support

- Single-event upset risk to avionics can lead to loss of vehicle
- Response to radiation event can delay launch

Aeronautics

- Communications interference or loss
- Risk to avionics
- Enhanced radiation exposure to crew of high or frequent flier

Principles of Radiation Protection

Radiation of biological concern to the human spaceflight program is primarily **"ionizing radiation"**

Ionizing radiation is produced by energetic 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);
- 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

- 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

Sources of Ionizing Radiation: Solar Particle Events

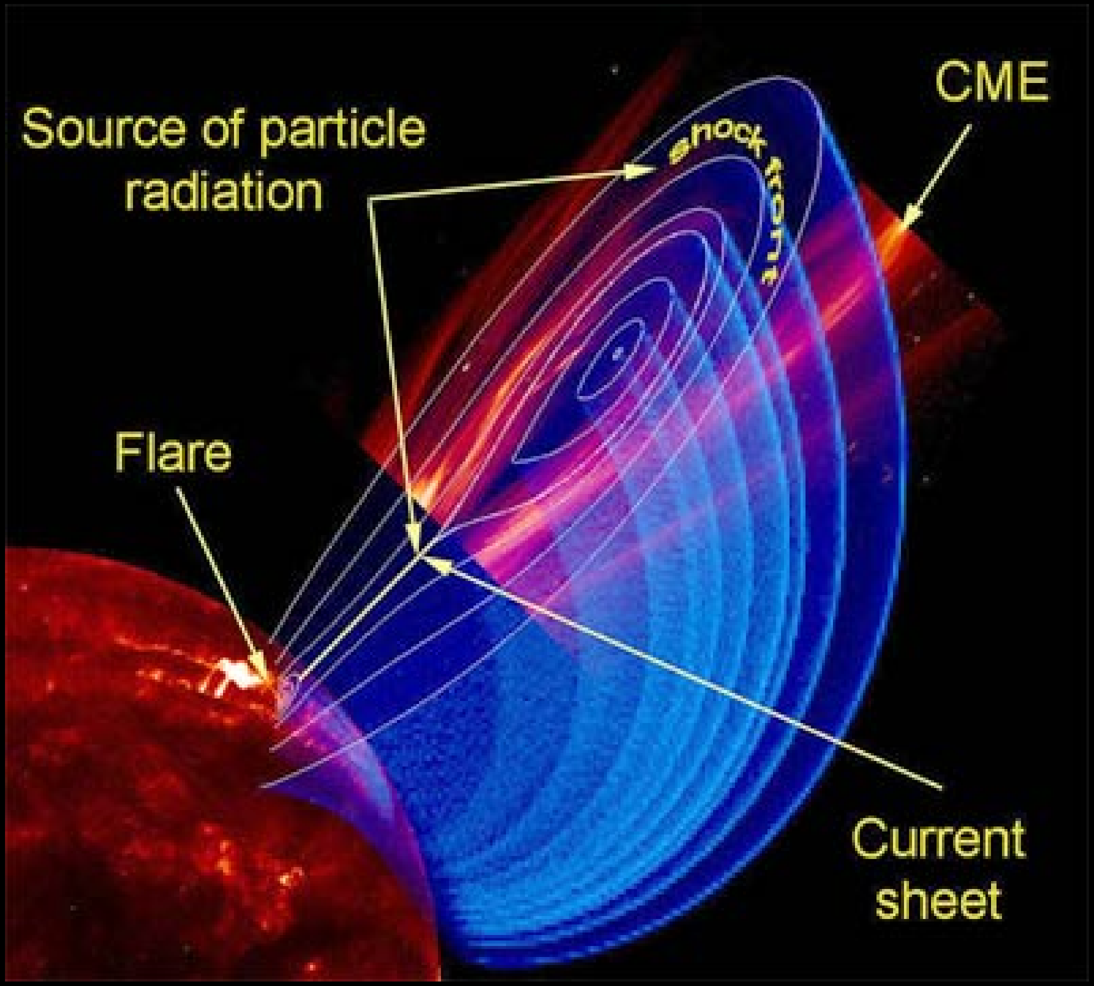
Solar Energetic Particles (SEPs):

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



Why Characterize Radiation Sources?

To understand risks to:

Astronauts

Radiation Poisoning from sudden events

Heightened long-term risk

Cancer

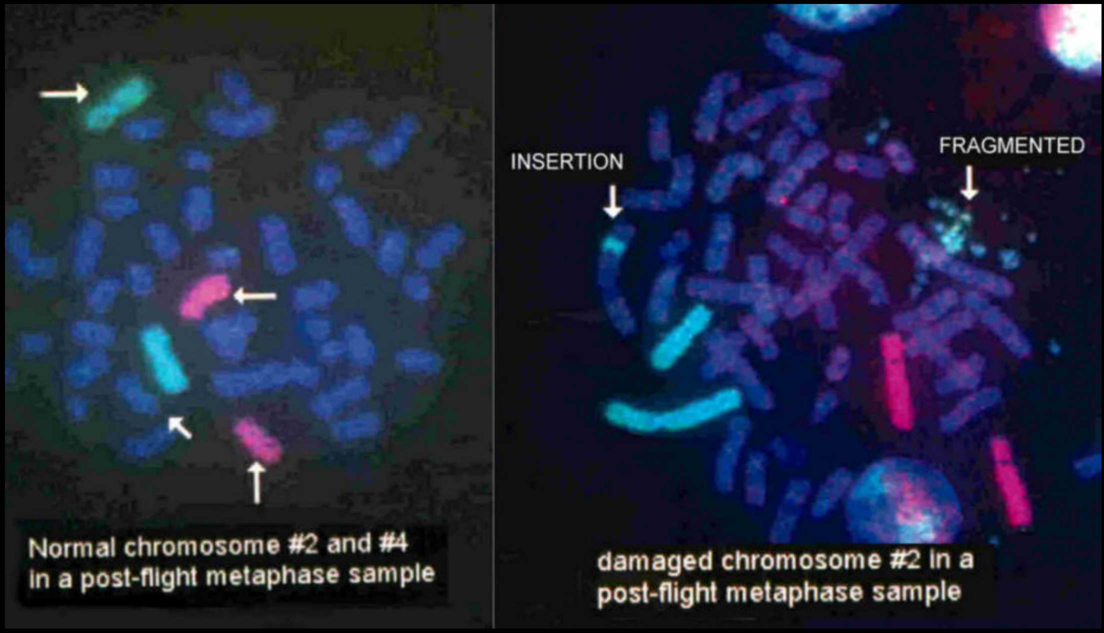
Cataracts

Spacecraft examples

Single event upsets

Attitude (Sun pulse & star tracker)

Radiation damage



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

Solar Radiation Storms (Energetic Particles)

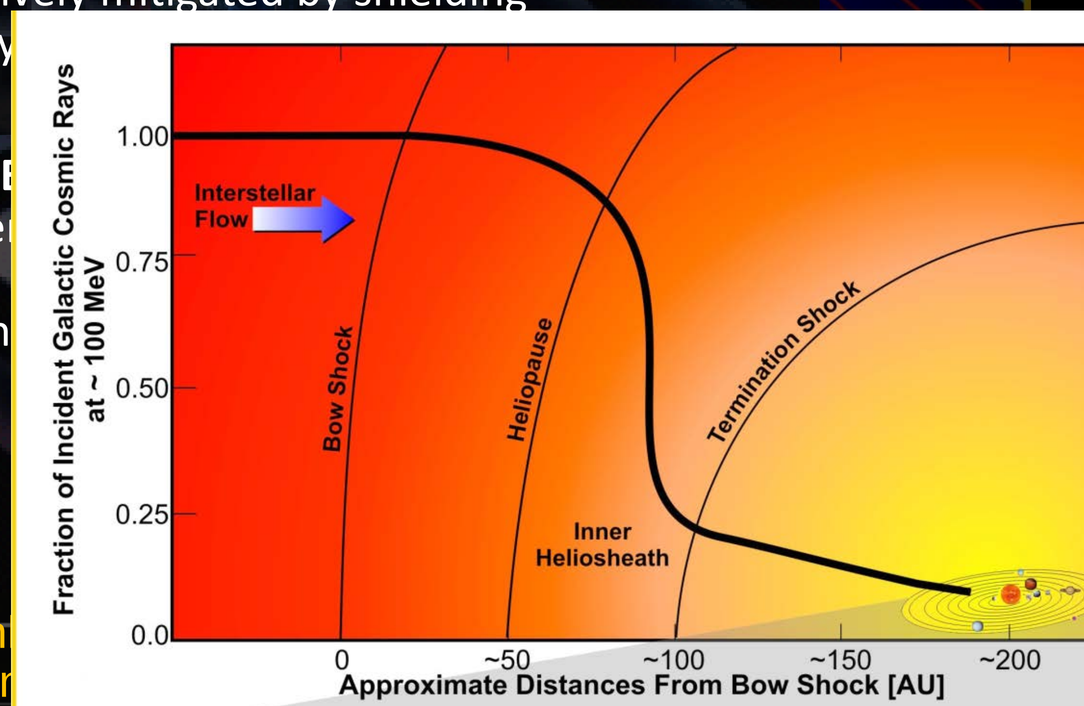
	Solar Radiation Storms	Flux level of >10 MeV protons	Frequency of Occurrence
Extreme **S5**	**Biological:** unavoidable high radiation hazard to astronauts on EVA (extra-vehicular activity); high radiation exposure to passengers and crew in commercial jets at high latitudes (approximately 100 chest x-rays) 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

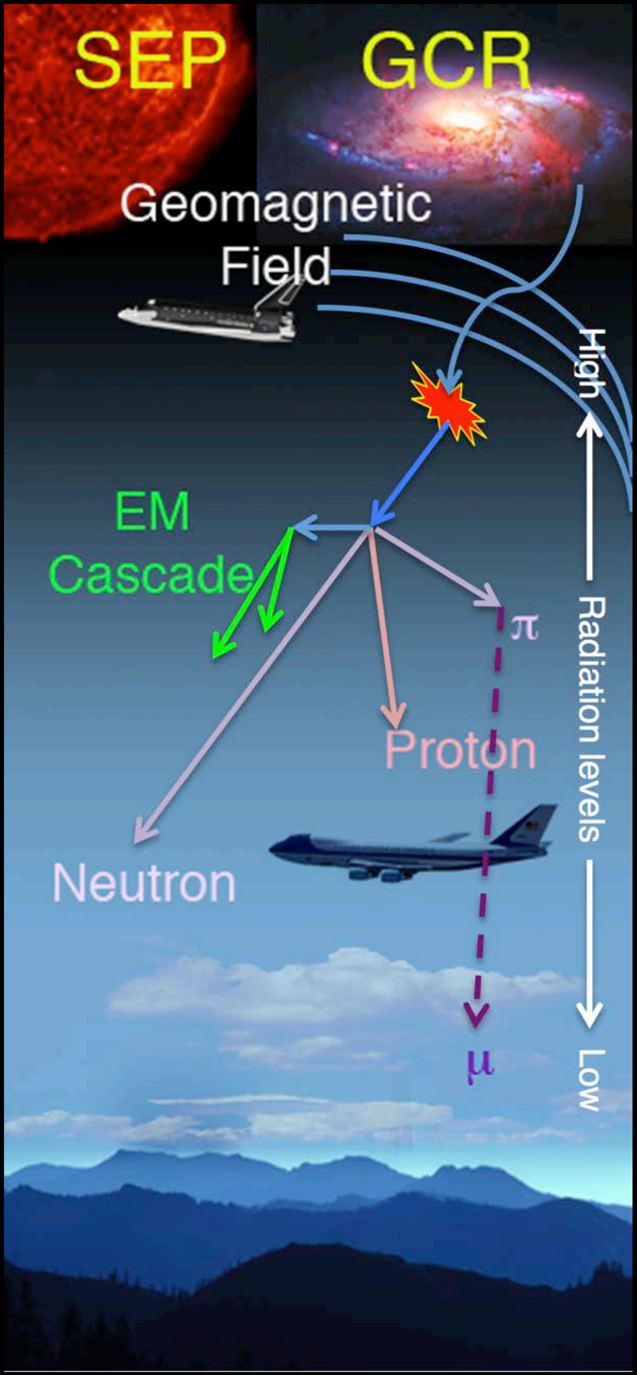
The Space Radiation Environment

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
- mainly
- MAIN

Galactic Cosmic Rays (GCR)
- high energy protons
- **highly charged, energetic atomic nuclei (HZE**
- not effectively shielded (break up into lighte
- abundances and energies quite well known
- MAIN PROBLEM: biological effects poorly un
- term space radiation hazard .
- Measure cosmic ray particles with energies
- also heavy ions, electrons, and neutrons
  - *Galactic cosmic rays – GCRs*
  - *Solar energetic particles– SEPs*
- Need accurate LET spectrum is missing lin
- and radiation biology to aid safe exploratio





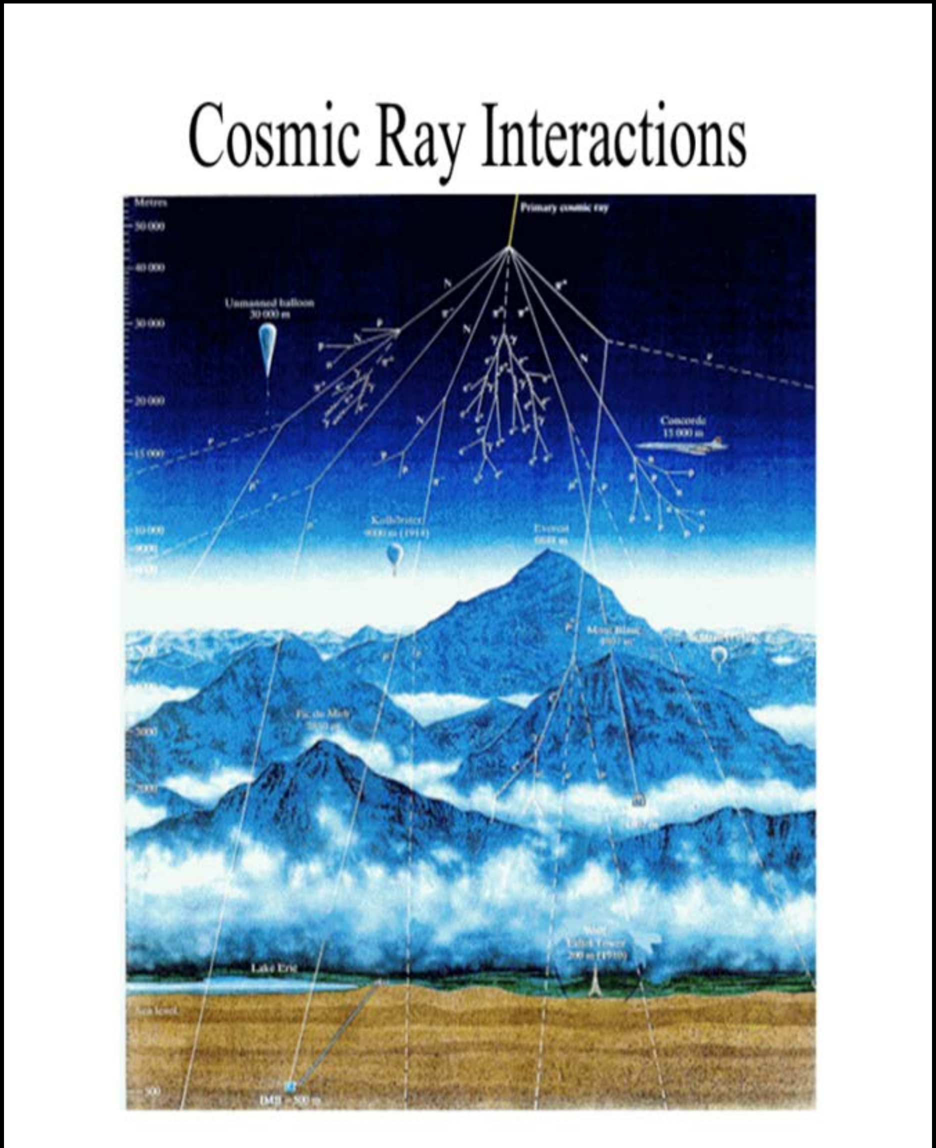
Space weather creates a dynamic radiation environment at aviation altitudes

Aviation radiation sources

- ✓ **global phenomenon** GCRs (career health issue and avionics SEUs)
- ✓ **high latitude phenomenon**
  - ✓ **Extended major events** SEPs (fleet operations and aircrew/passenger safety issue)
  - o **Short-term minor events** precipitating outer radiation belt energetic electrons (career health issue)
  - o **Instantaneous minor events** terrestrial gamma-ray flashes (TGFs) (avionics EMI)

Aviation Radiation Health Effects

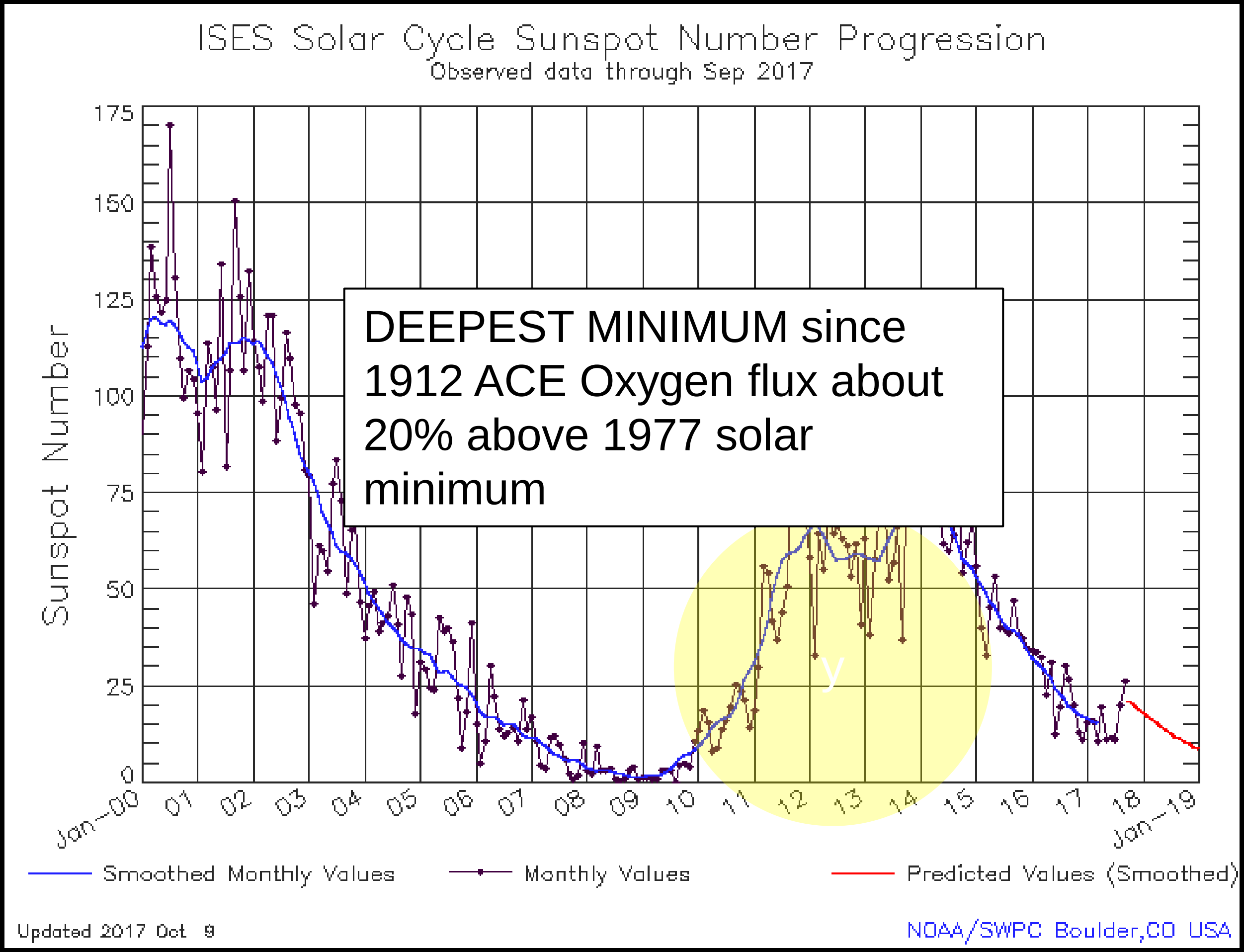
- Cosmic rays **(CR)** are the primary source of ionizing radiation that increases risk of fatal cancer or other adverse health effects to air travelers
- **Commercial aircrews are classified as radiation workers** (ICRP, 1990)
  - Most exposed occupational group (NCRP, 2009)
  - Individual career and storm exposures unquantified and undocumented
- NIOSH pregnant female flight attendant epidemiological studies (Grajewski et al., 2015)
  - **70% increased risk of miscarriage in first trimester due to CR**
- **Maximum public and prenatal exposure easily exceeded** (ICRP recommendations)
  - One high-latitude solar storm event
  - Frequent use of high-latitude routes (~5-10 round-trips)
- Equivalent Flight Exposures
  - **Round-trip international ~ 2 chest x-rays**
  - **100k mile flyer ~ 20 chest x-rays (2 mSv) = 2 x DOE limit**

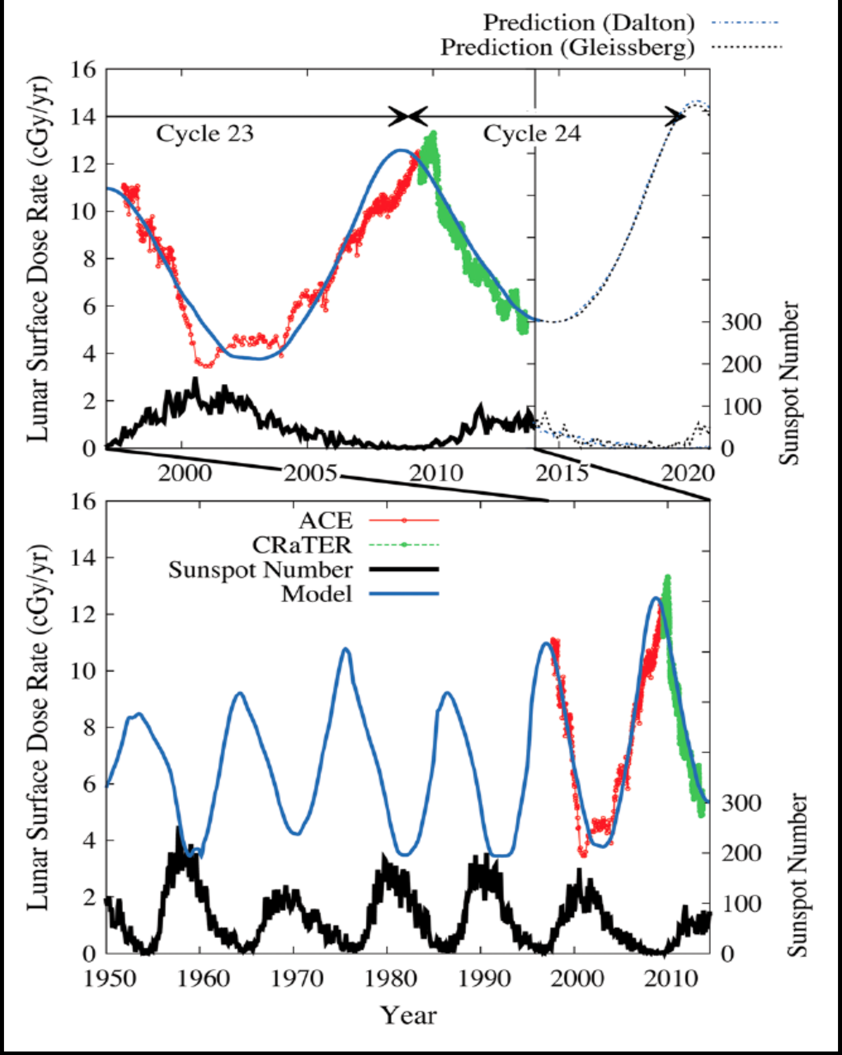


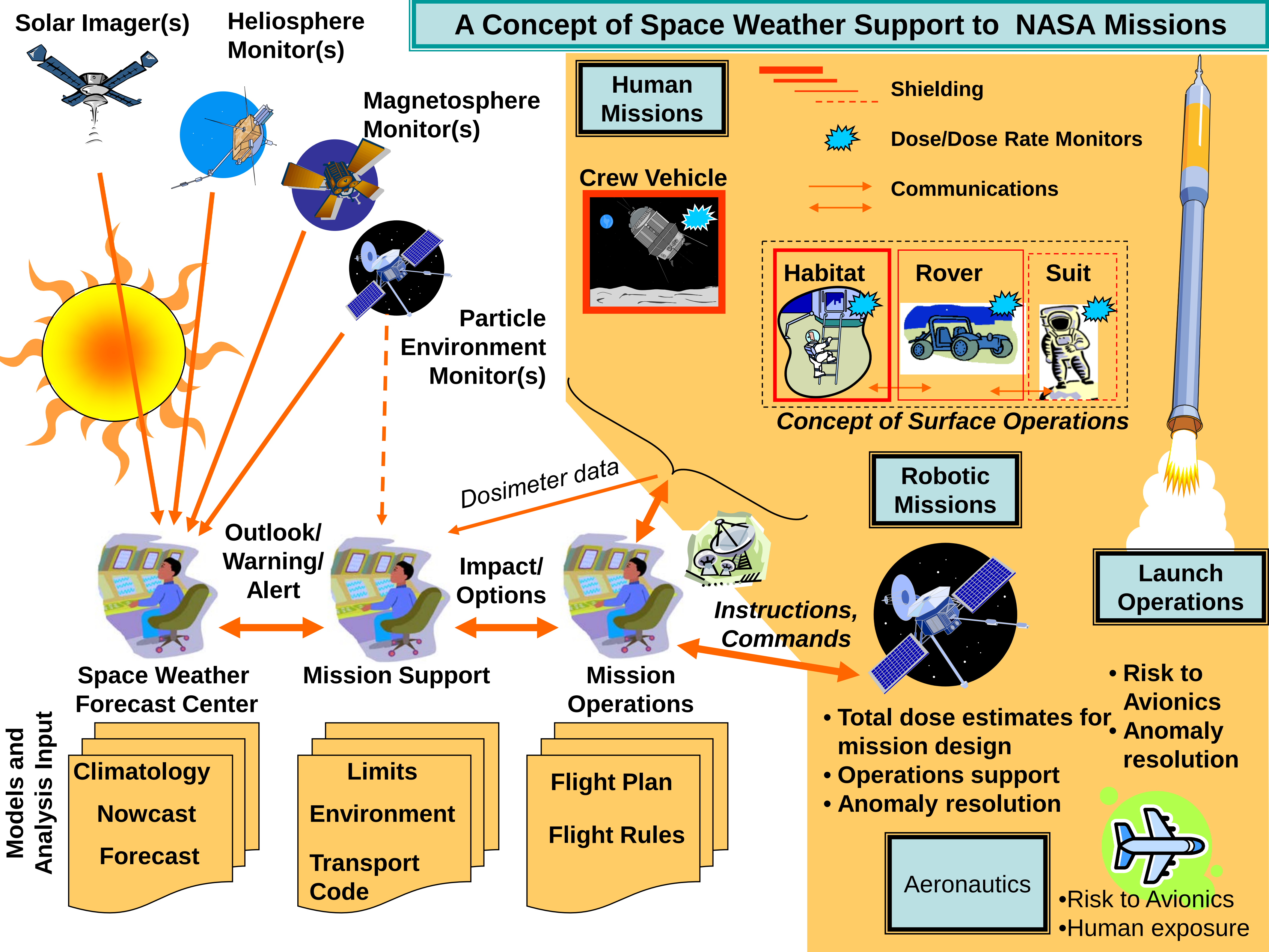
Aviation Radiation Avionic Effects

- **CR effects on Avionics Systems**
  - **CR** interact with semiconductor material, depositing charge causing single event effects (**SEE**) → change in logic state
  - Number of recorded instances of avionic **SEE** at GCR exposure levels (e.g., Normand et al., 1997, 2001; Olsen et al., 1993)
  - **SEE** in autopilot systems correlated with CR flux (altitude and latitude variation)
  - Avionics **SEE** occurrence rate (RAE, 2013)
    - **GCR: every 200 flight hours**
    - **Solar storm: > 1 per hour (scaled Feb 1956 event)**
  - **Near catastrophic event**: Qantas flight 72, October 7, 2008 (pictured right)
    - SEE most probable explanation. All other environmental causes ruled out (ATSB, 2011)
    - Intermittent, incorrect inertial reference data initiated violent pitch-down command from flight control system
    - **110/303 passengers and 9/12 crew injured; 12 occupants seriously injured; 39 received hospital treatment**
- **For aircraft systems (as opposed to components) radiation standards and industry awareness less developed**
  - Guidance standards only
  - No regulatory standards

ISSUES - Deepest Minimum, Future GCR Flux







A Concept of Space Weather Support to NASA Missions
Solar Imager(s)
Heliosphere Monitor(s)
Magnetosphere Monitor(s)
Particle Environment Monitor(s)
Human Missions
Crew Vehicle
Shielding
Dose/Dose Rate Monitors
Communications
Habitat
Rover
Suit
Concept of Surface Operations
Dosimeter data
Robotic Missions
Launch Operations
Outlook/ Warning/ Alert
Impact/ Options
Instructions, Commands
Space Weather Forecast Center
Mission Support
Mission Operations
Models and Analysis Input
Climatology
Nowcast
Forecast
Limits
Environment
Transport Code
Flight Plan
Flight Rules
• Total dose estimates for mission design
• Operations support
• Anomaly resolution
• Risk to Avionics
• Anomaly resolution
Aeronautics
•Risk to Avionics
•Human exposure

Terrestrial Weather

Awareness — **Recognition** — **Reporting** — **Short term, Useful Forecasts** — **Longer Term, Greater Sophistication**

BC //

17th Century
barometer
thermometer
hygrometer
anemometer

1750
Ben Franklin
synoptic studies of storm systems

1850s
compiled area-wide observations

1920s
Polar front theory of extra-tropical cyclones

1940s
World War II

1950s + ⟹
Computer Age

1960s+ ⟹
Space Age

Space Weather

Awareness — **Recognition** — **Reporting** — **Short term, Useful Forecasts** ⟹

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15h Century
Sunspot Observations

18th/19th Centuries
Magnetometers

1840s
Telegraph Impact

1859
Carrington Event

19th/20th Centuries
Networked Magnetometers, Aurora, Sunspots, Flares

1940s
World War II

1950s + ⟹
Computer Age

1960s+ ⟹
Space Age

Workshop Overview

The agenda encourage a robust exchange of ideas between various disciplines of interest. Following plenary sessions, which was selected to provoke new ideas and creative dialogue, breakout groups were formed to develop new approaches to radiation measurement and modeling for a range of environmental contexts, including aviation altitude, LEO, and deep space habitats.

The goal of the breakout groups was to develop approaches for distributed radiation observations built around specific scenarios, with the purpose of providing focus as well as eliciting innovative ideas. A summary report-back by each group focused on technical findings, with emphasis on radiation challenges and corresponding notional solutions.

“Domain” and “Scenario”

- The overview chart broadly defines the Domain of the Working Group
- Concept Charts ask for a Scenario
- A “Scenario” is the specific problem or topic within the “Domain” that proposed concepts are meant to address
- Examples:
  - Domain: Aviation altitudes
    - Scenario: Passenger/Crew exposure in response to a solar event
    - Scenario: Characterize the cut-off rigidity for multiple magnetic latitudes/longitudes
  - Domain: Deep Space
    - Scenario: Cis Lunar Space, +/- 0.1 AU from Earth
    - Scenario: Characterize an SPE over 10s of degrees of heliolongitude/heliolatitude at one or more distances from the sun
  - Domain: Deep Space Habitat
    - Scenario: Deep Space Gateway Habitat
    - Scenario: Lunar Surface architecture elements for human exploration

Examples of Concepts (1)

- Domain: Aviation altitudes
- Senario: Passenger/Crew exposure in response to a solar event
- Concept: Dosimetry in Commercial Aircraft
- Innovation: Realtime data downlink from active dosimeters in aircraft galleries
- Impact: Thousands of records nationwide (worldwide)

Examples of Concepts (2)

- Domain: Deep Space
- Scenario: Characterize an SPE over 10s of degrees of heliolongitude/heliolatitude at one or more distances from the sun
- Concept: Hundreds of MicroChips over dispersed over vast areas, each sensitive to one or more threshold proton energies; Relatively few small sat communication nodes to relay data to Earth
- Innovation: Simplified integral energy measurements over extent of SPE
- Impact: Near complete characterization of evolution of SPE

Aviation

- Biggest challenge: - lack of data from flight
- Need – data: 4 Dimensions-
- Goal: airlines to carry sensors to provide these measurements

Deep Space

Biggest challenge: - lack of data from real environment

Need – data: multidimensional

Goal: amplification of data collection

Suborbital Commercial Space Transportation

- The pending advent of commercial suborbital human spaceflight raises some new challenges for the space weather community
- While the radiation exposure on short suborbital flights will be minimal, there is still a need to:
  - Provide passengers and crew with enough information to support “informed consent”
  - Monitor the environment inside the vehicle
- Compare the measurements with expected exposure
- Areas for potential development include:
  - Development of light-weight, comprehensive radiation monitors (especially neutrons under shielding)
  - Models of the radiation environment in the 50-120 km range, both natural and under typical shielding
  - Models of the exposure vs latitude, under shielding, during modest to severe solar events
  - Measurements of the radiation in this regime to validate the exposure

Presidential Space Policy Directive (SPD) 1

On Dec. 11, 2017 President Trump signed SPD 1 that directed NASA to “Lead an **innovative** and **sustainable** program of exploration with **commercial and international partners** to enable human expansion across the solar system and to bring back to Earth new knowledge and opportunities. Beginning with missions beyond low-Earth orbit, the United States will lead the return of humans to the Moon for long-term exploration and utilization, followed by human missions to Mars and other destinations;”