NEXT GENERATION IONIZING RADIATION CHARACTERIZATION FROM AVIATION ALTITUDE TO DEEP SPACE

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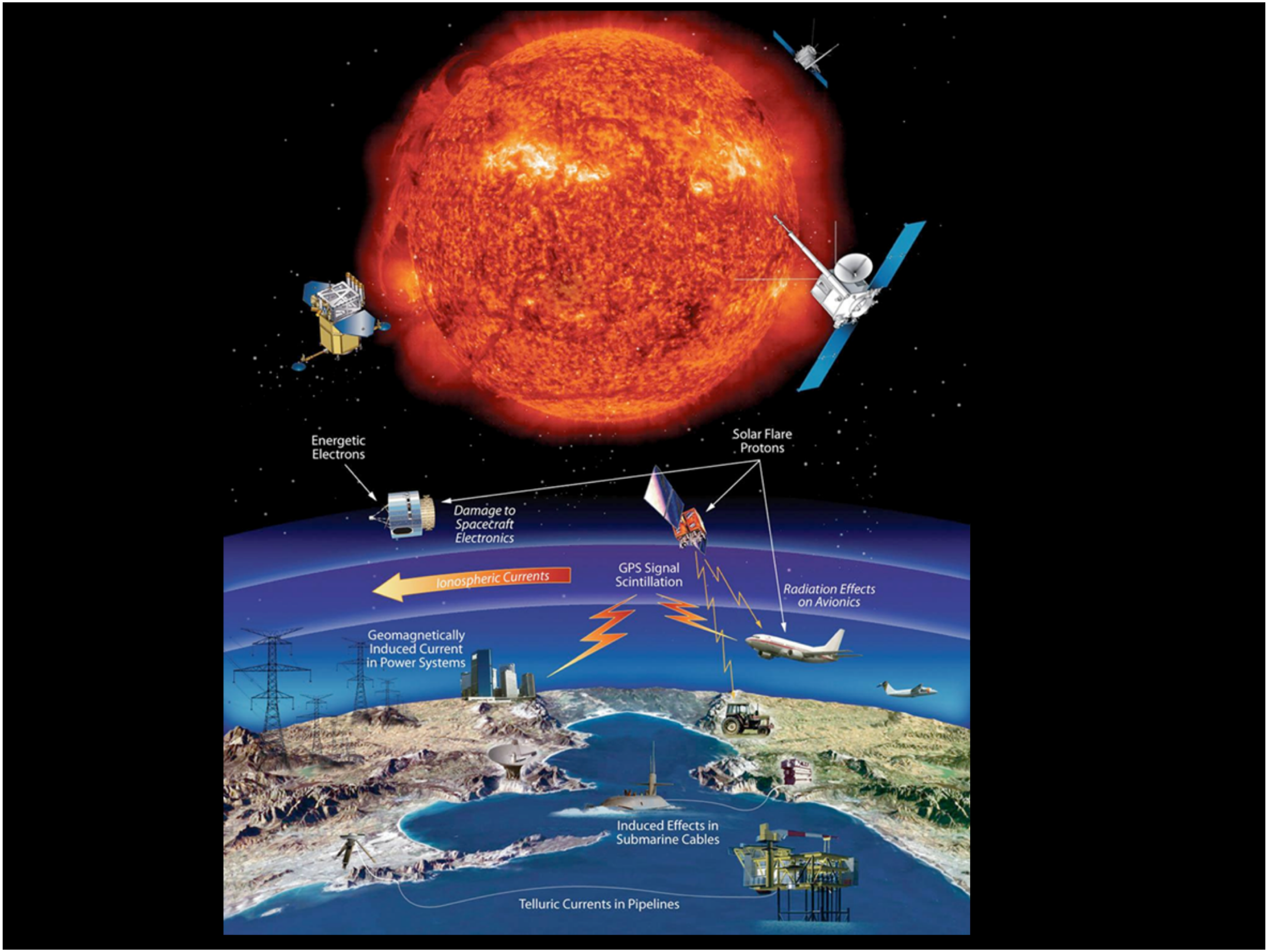


Energetic Electrons
Solar Flare Protons
Damage to Spacecraft Electronics
GPS Signal Scintillation
Ionospheric Currents
Radiation Effects on Avionics
Geomagnetically Induced Current in Power Systems
Induced Effects in Submarine Cables
Telluric Currents in Pipelines

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

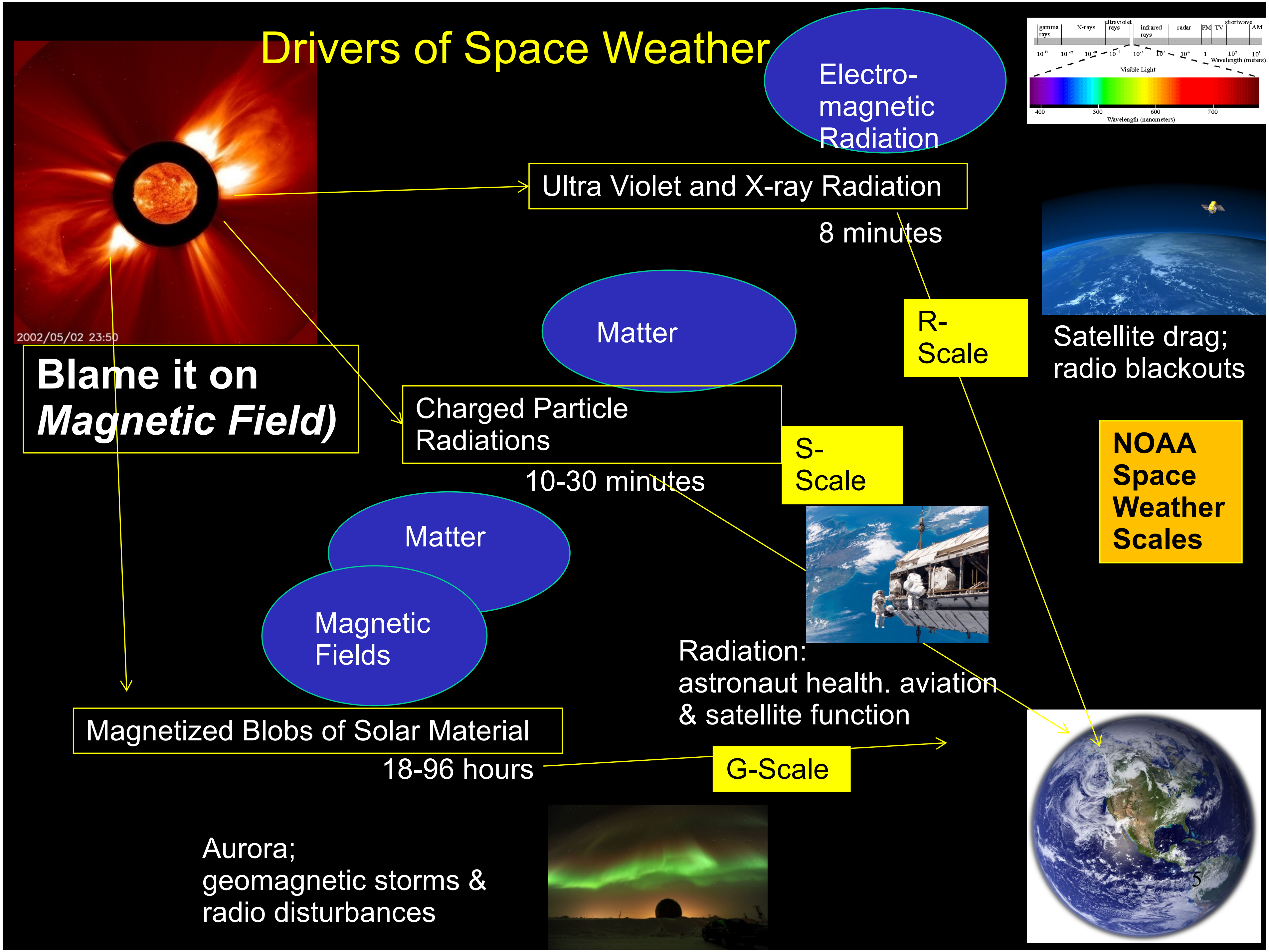
Space Weather

For the purpose of this report, “space weather” refers to conditions of the space environment and includes short term fluctuations (meteorology) as well as long term averages and extremes (climatology)

The space environment extends from the Sun through the heliosphere andi ncludes the magnetospheres and ionospheres of planets and moons of the solar system

The space environment is characterized by the magnetic fields, charged and neutral components of the solar wind, and solar energetic particles superimposed on the solar wind from solar and galactic sources

The space environment changes over time scales ranging from seconds to millennium, but the most common time scales of interest to operations range from minutes to hours or days; for mission planning and design the relevant time scales range from days to years or decades



Drivers of Space Weather
Electro-magnetic Radiation
gamma rays
X-rays
ultraviolet rays
infrared rays
radar
FM
TV
shortwave
AM
Wavelength (meters)
Visible Light
400
500
600
700
Wavelength (nanometers)
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Ultra Violet and X-ray Radiation
8 minutes
R-Scale
Satellite drag; radio blackouts
Matter
Blame it on Magnetic Field)
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

- Kep 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

Sources of Ionizing Radiation: Solar Particle Events

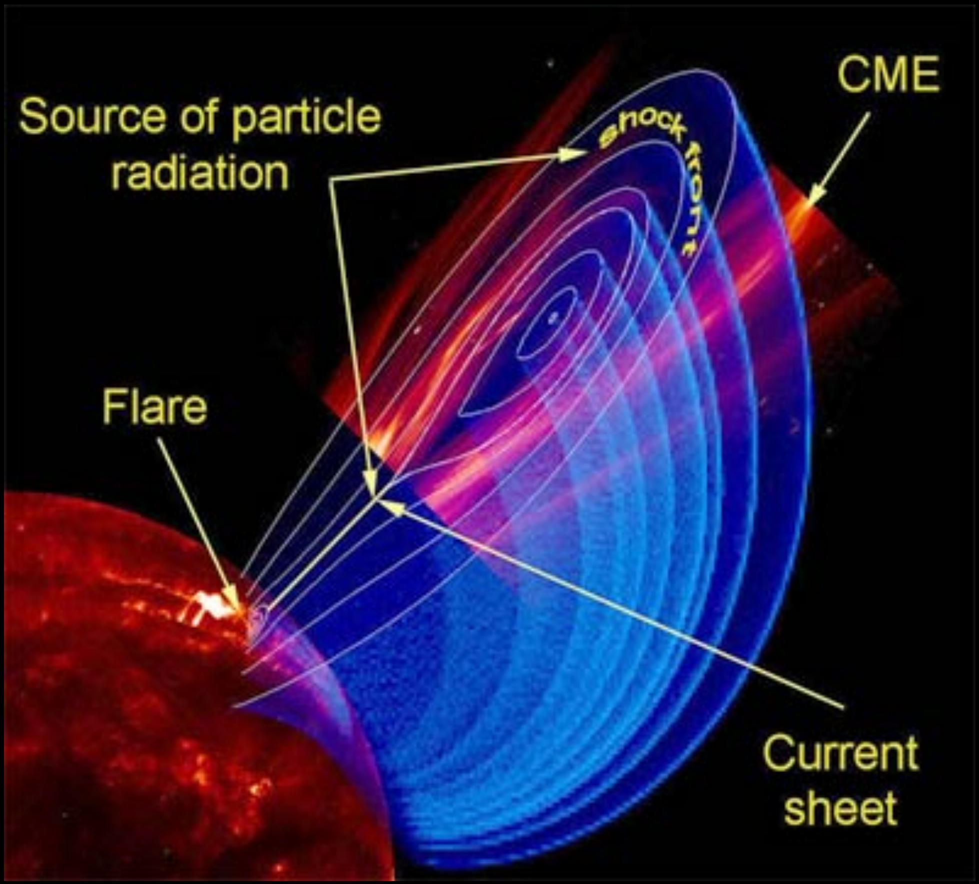
Solar Energetic Particles (SEPs):

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:

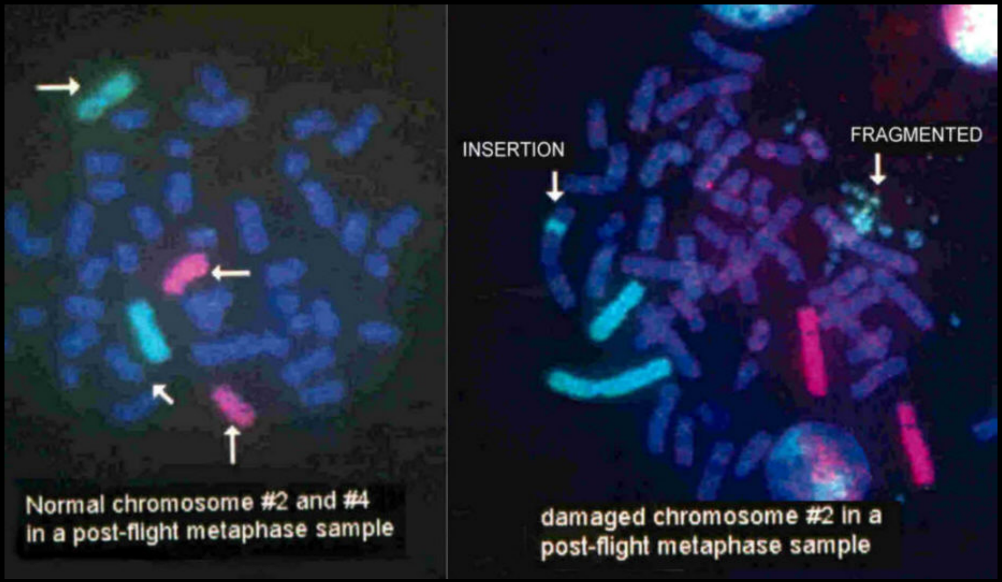
Astronauts

Radiation Poisoning from sudden

Heightened long-term risk

Cancer

Cataracts



Spacecraft examples

Single event upsets

Attitude (Sun pulse & star tracker)

Radiation damage

Magnitude and Scope of Effects?

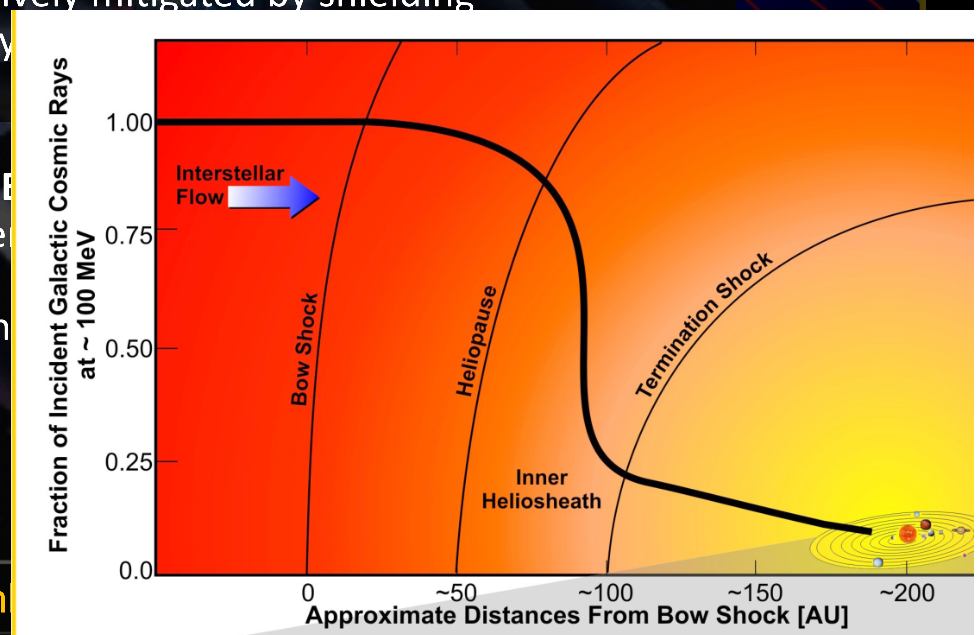
- ISS: 1 REM (Roentgen Equivalent Man, 1 REM ~ 1 CAT Scan)
  - Scintillations
  - Hardened shelter
- Spacesuit on Moon 50 REM (Radiation sickness)
  - Vomiting
  - Fatigue
  - Low blood cell counts
- 300 REM+ suddenly
  - Fatal for 50% within 60 days
- Also
  - Two communication satellites lost
  - Airplanes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

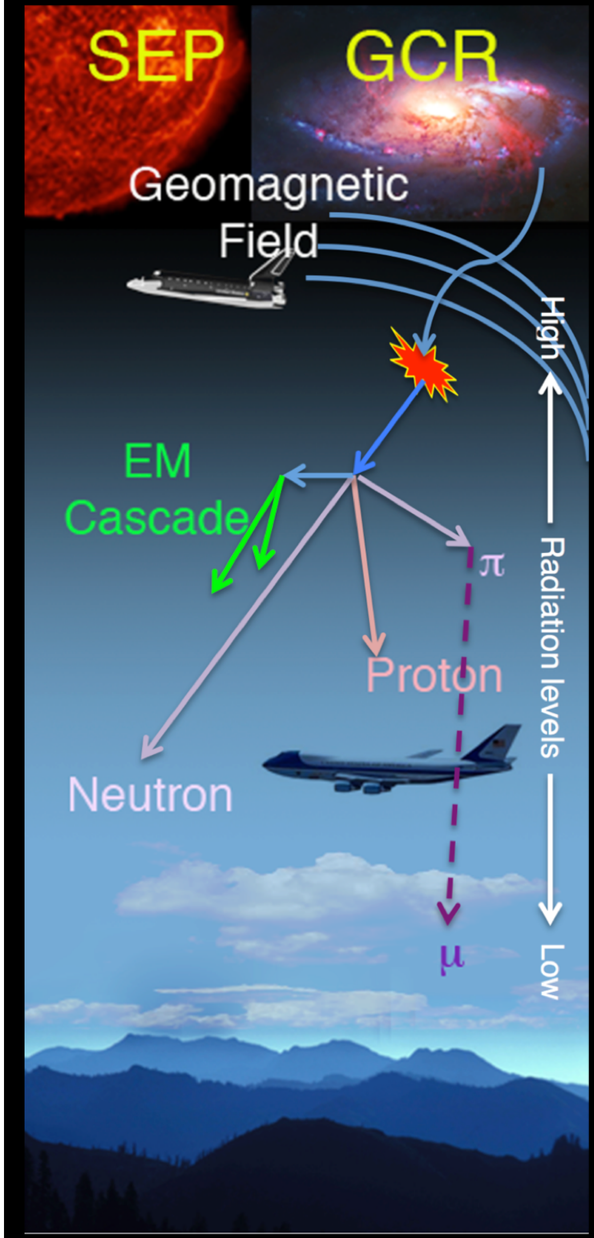
The Space Radiation Environment

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 exploration





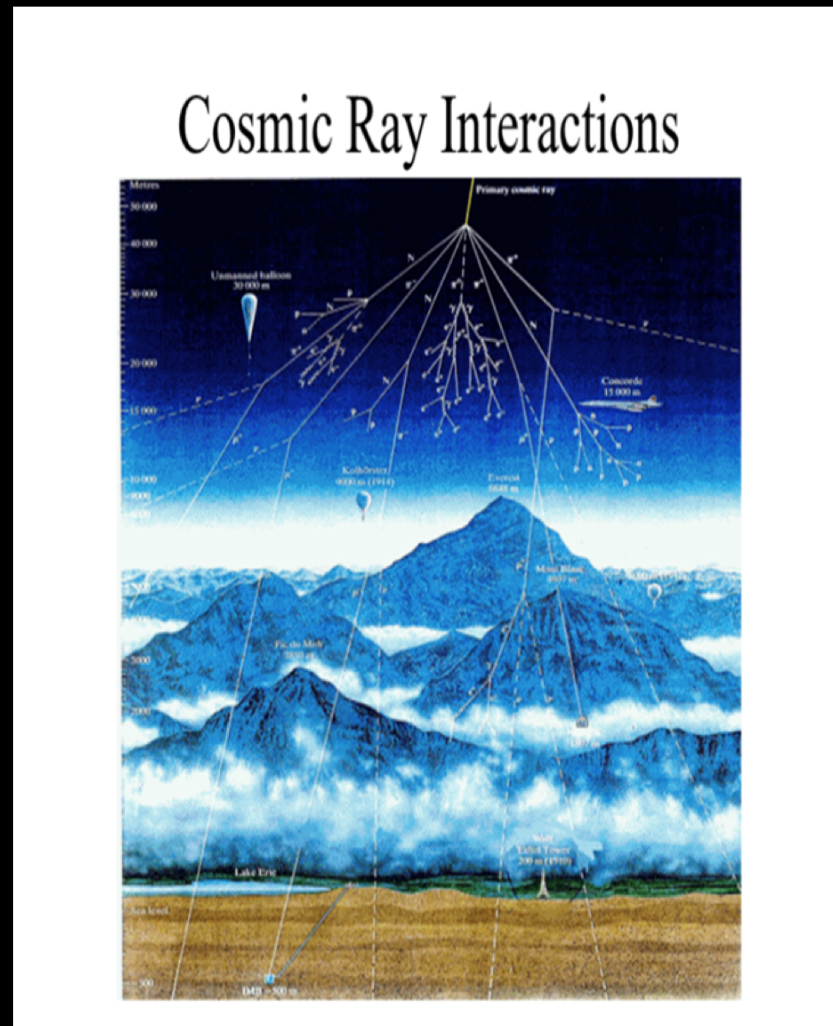
Space weather creates a dynamic radiation environment at aviation altitudes

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)
  - ○ **Short-term minor events** precipitating outer radiation belt energetic electrons (career health issue)
  - ○ **Instantaneous minor events** terrestrial gamma-ray flashes (TGFs) (avionics EMI)

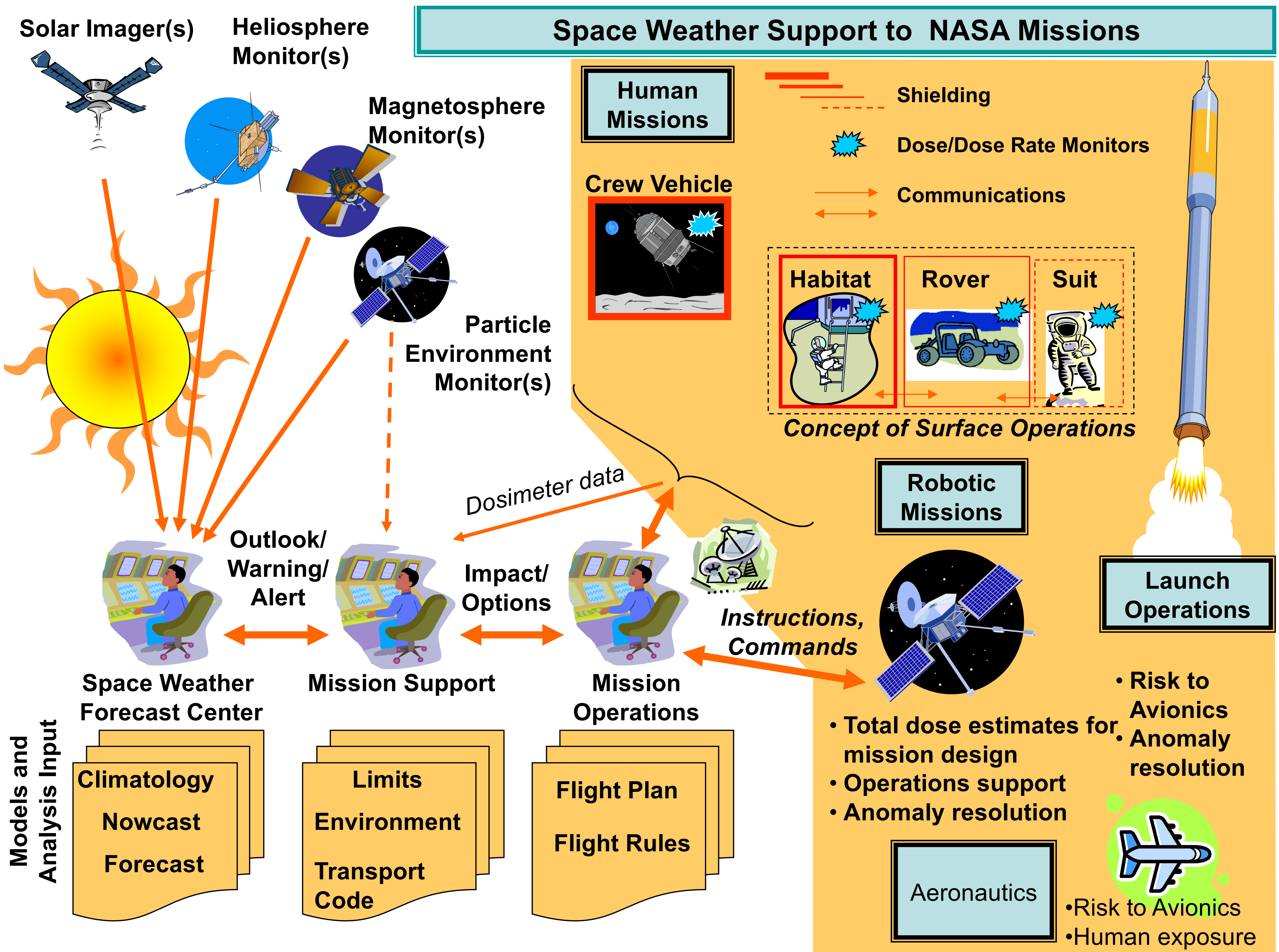
Aviation Radiation Health Effects

- 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**

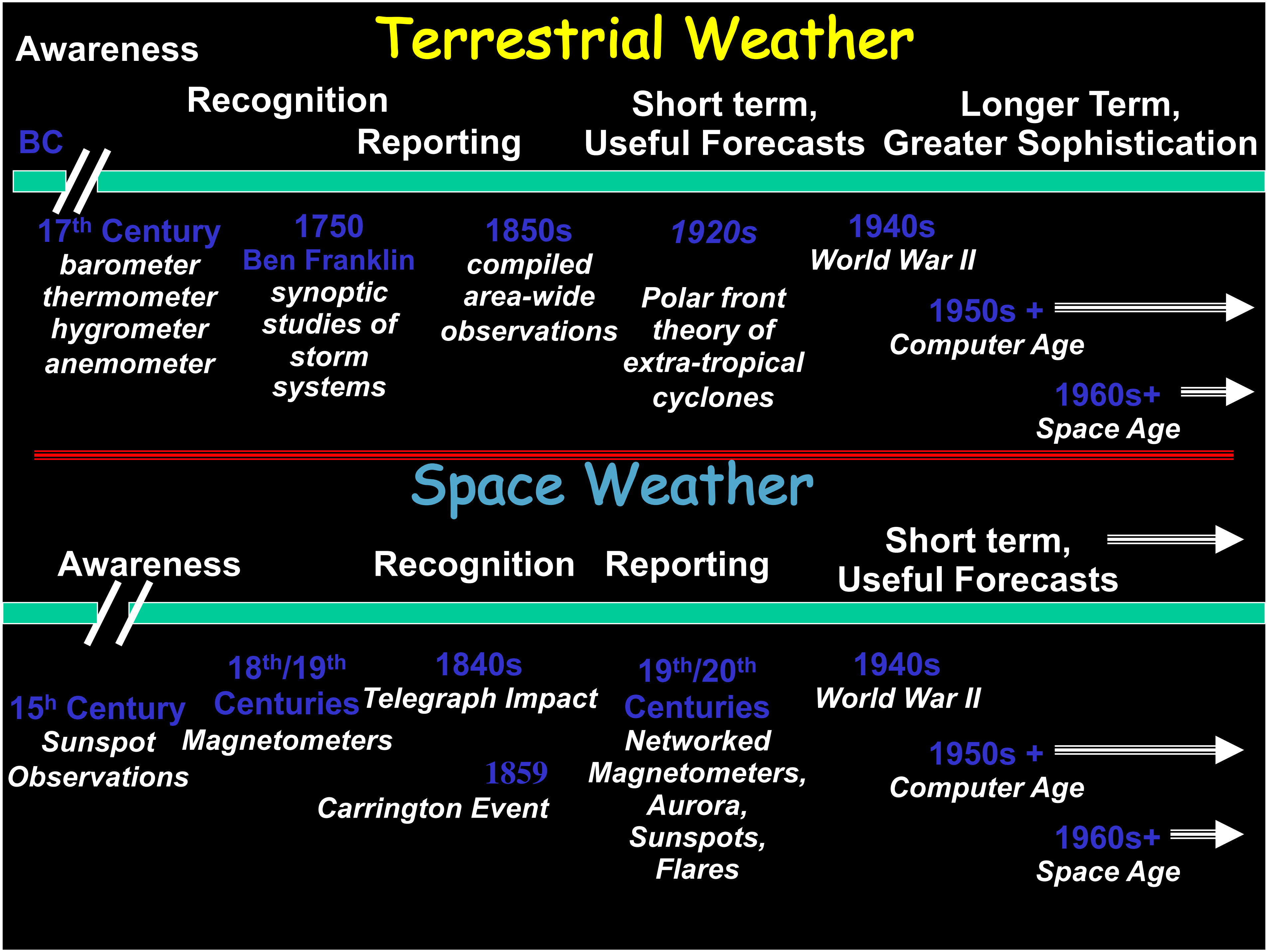


Aviation Radiation Avionic Effects

- **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



Space Weather Support to NASA Missions
Solar Imager(s)
Heliosphere Monitor(s)
Magnetosphere Monitor(s)
Particle Environment Monitor(s)
Human Missions
Shielding
Dose/Dose Rate Monitors
Communications
Crew Vehicle
Habitat
Rover
Suit
Concept of Surface Operations
Robotic Missions
Launch Operations
Dosimeter data
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
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.

Expected Outcomes

The goal of this invited technical workshop was to explore ways to enable data-rich characterization, forecasting and monitoring of space radiation environment relevant to NASA science, aviation and deep space exploration.

The outcome of this workshop will inform the development of one or more FY 2019 calls for proposals for radiation detection sensors, analytic models and/or other enabling technologies that can be applied to ionizing radiation at altitudes ranging from near-Earth to cis-lunar and beyond.

A unique aspect of this workshop was to combine invited participation from traditional NASA technology, science and engineering communities with participants from non-NASA organizations with relevant technologies not previously applied to space mission applications.

“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
- Scenario: 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

Working Group One: Aviation Overview

Topic Area Scope

- Reduce radiation hazard risks for the aviation community related to human tissue exposure and SEUs in avionics
- Extending the assessment to higher altitude in anticipation of future aviation operations
- Accumulated exposure for high altitude platforms/drones

Typical Approaches Today

- Ignore radiation issues
- Use NOAA S-scale for risk management decision aid tool
- Use HF comm accessibility as a proxy for radiation environment
- Use CARI-6 radiation model output

State of the Art

- Modeled global radiation
  - NAIRAS
  - CARI-7
  - PANDOCA
  - KREAM
- Aircraft radiation measurements
  - ARMAS
  - TEPC

Challenges/Gaps

- Measuring along relevant flight paths (time, location, geomagnetic conditions) inadequate characterization of the environment incl extreme events
- Capturing extreme events such as SPEs
- Going beyond climatology to obtain radiation weather
- Comprehensive Modeling V&V (GCR/SEP)
- Develop confidence level on SEP model predictions

Working Group One: Aviation Altitude Concepts

Scenario

- Comprehensive physics-based model benchmarks and V&V (particle spectra, dosimetry, multiple cutoffs and altitudes 8 km to LEO)
- Measuring along relevant flight paths (time, location, geomagnetic conditions)
- Capturing extreme events such as SPEs
- Going beyond climatology to obtain radiation weather

Concept

- Model intercomparisons for benchmarks and comparisons to current measurements databases (ARMAS, RaD-X, ER-2, BESS, CAPRICE, AMS-02, ICRP/ICRU)
- Statistical analysis of time-dependent SEP events to establish confidence level for real-time predictions
- Transition physics-based models (NAIRAS) to CCMC for model independent benchmarking and V&V, pathway to operations
- Real-time measurements aboard aircraft
- Continuous radiation monitoring
- Data assimilation of continuously monitored radiation data into physics-based models such as NAIRAS

Innovation

- Comprehensive assessment cosmic radiation transport physics and dosimetry
- Iridium and/or WiFi transmitted measurements from aircraft in real-time to operational servers
- Loiter capabilities with radiation monitors using high altitude balloons and/or multiple commercial aircraft over NoPAC and NAT routes

Impact and Benefit

- Ability to accumulate data for use in assimilation scheme
- Increased probability of capturing SPEs and their effects
- Validated and reliable decision aid tools that can be built for global aviation radiation weather for ATC and pilot use

Working Group Two: Deep Space Overview

Topic Area Scope

Define space environment beyond LEO

- GCR
- SEP
- Solar wind
- Interplanetary magnetic field

Typical Approaches Today

Modeling (empirical / forecast):

- SEPs
- Electrons (Posner model)
- GCR models (DLR, BO, CREME96)

Modeling (particle acceleration & transport through heliosphere)

- Proprietary models

State of the Art

- Species from H to Zn (Z: 1-28)
- Energy range: 10 MeV/n to 10s of GeV/n (ACE & AMS assets)
- Electrons (E range: 100s keV to GeV)
- Photons (E range: keV to GeV)
- Interplanetary magnetic field (0.3 to 10 AU & >128AU)
- Space location:
  - 1AU (*e.g.*, ACE & AMS)
  - Historical: Ulysses (up to 5AU), Voyager and HELIOS
  - STEREO (1AU)

Challenges/Gaps

- Z > 28 (>100 MeV/n)
- Temp/spatial variability of low-energy protons & light ions (<10 MeV/n)
- Temp/spatial variability of ions > 400 MeV/n
- SPEs out of ecliptic plane & longitudinal variation
- Small satellite technologies (*e.g.*, propulsion, communications, GNC, ADC, power)
- Onboard processing
- Industry participation lacking
  - *e.g.*, grand challenge X-prize SPE prediction
  - Big data: AI & machine learning
- Societal awareness of impact of space environment

Working Group Two: Deep Space Concepts

Scenario

Heliosphere space-weather array

Concept

Small satellite constellation (100s) to map the heliosphere (characterize temporal-spatial & composition of radiation and plasma environment) throughout the inner Solar system.

Innovation

- Low-cost launch-ready instruments (*e.g.*, mag, energetic particles, cosmic rays) pre-built in small satellites for opportunistic launch opportunities
- Low-power instrument to measure ALL element species >100 MeV/n
- Extensive data on temporal-spatial variability of all ions and energy ranges
- Comprehensive data set on SPEs out of ecliptic plane & longitudinal variation
- Advancement of propulsion, GNC, ADCS, and communication technologies for small satellites beyond 1AU
- Big data: AI & machine learning applied to the abovementioned data sets

Impact and Benefit

- Network of distributed point measurements of particles and magnetic fields 0.1-0.3AU for modeling and forecasting applications
- Better space environment characterization
- Inform mission operations for robotic and human missions
- Terrestrial operations

Working Group Two: Deep Space Concepts

Scenario

Characterization of global heliospheric boundaries & structure from distributed point measurements

Concept

Small satellite constellation (100s) to characterize the temporal-spatial structure of the heliosphere boundaries & interstellar medium.

Innovation

Advancement of propulsion, power, and communication technologies for small satellites beyond 1AU
Reliability (and/or redundancy) of spacecraft systems & subsystems for long-duration missions

Impact and Benefit

First distributed in situ measurements of heliospheric boundaries and interstellar medium
Understanding of GCR modulation through global heliosphere
Tech demonstration of small satellite propulsion, communications, and power technologies (and reliability)
Better space environment characterization
Inform mission operations for robotic and human missions

Working Group Two: Deep Space Concepts

Scenario

Interplanetary space-weather buoy co-orbiting with Mars

Concept

Satellite to characterize solar winds, magnetic fields, particle energies (protons) & composition co-orbiting with Mars.

Innovation

First characterization of high-energy proton (10s of MeV) environment at 1.5 AU (*i.e.*, Mars orbit)

Enable data sets to improve near-Mars & interplanetary weather and climate models

Impact and Benefit

Extrapolation of solar proton environment to >1AU

Better space environment characterization

Inform mission design for robotic and human missions

Working Group Two: Deep Space Concept

Scenario

Magnetograph imaging of the poles and 360 of the Sun from small satellites for solar dynamo validation

Concept

Small satellites to remotely provide LOS magnetographs of the solar polar (2 satellites) and ecliptic regions (3 satellites)

Innovation

First imaging of extreme polar regions of the Sun
Advancement of propulsion, communication, and power technologies in small satellites

Impact and Benefit

Validation of dynamo model for long-term prediction of solar cycle
Constant observation of Sun's magnetic field
Modeling of GCRs
Validation of heliospheric models
Improvement of solar event prediction

Aviation

Biggest challenge: - lack of data from flight

Need – data: 4 Dimensions-

Goal: airlines to carry sensors to provide these measurements

Solution:

- RFI to get an understanding of best sensors available; process of miniaturization; meeting standards to fly on airplanes, etc – that also is followed up by an RFP
- In parallel release solicitation to identify external partnering organization (one not for profit and one for profit) – provide examples that already exist (NRA, tipping point from STMD, etc)
- Citizen science contributions

Deep space

Biggest challenge: - lack of data from real environment

Need – data: multidimensional

Goal: amplification of data collection

Solution:

- RFI to get an understanding of best sensing technology that can fit on a cube sat/small sat volume; miniaturization; integration, data collection and transmission; data hubs (HEX) – that also is followed up by an RFP
- Mechanism of partnership to fly on commercial space missions (piggy back vs dedicated mission capability); international partnerships

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;”