The Economic and Societal Impacts of Space Weather

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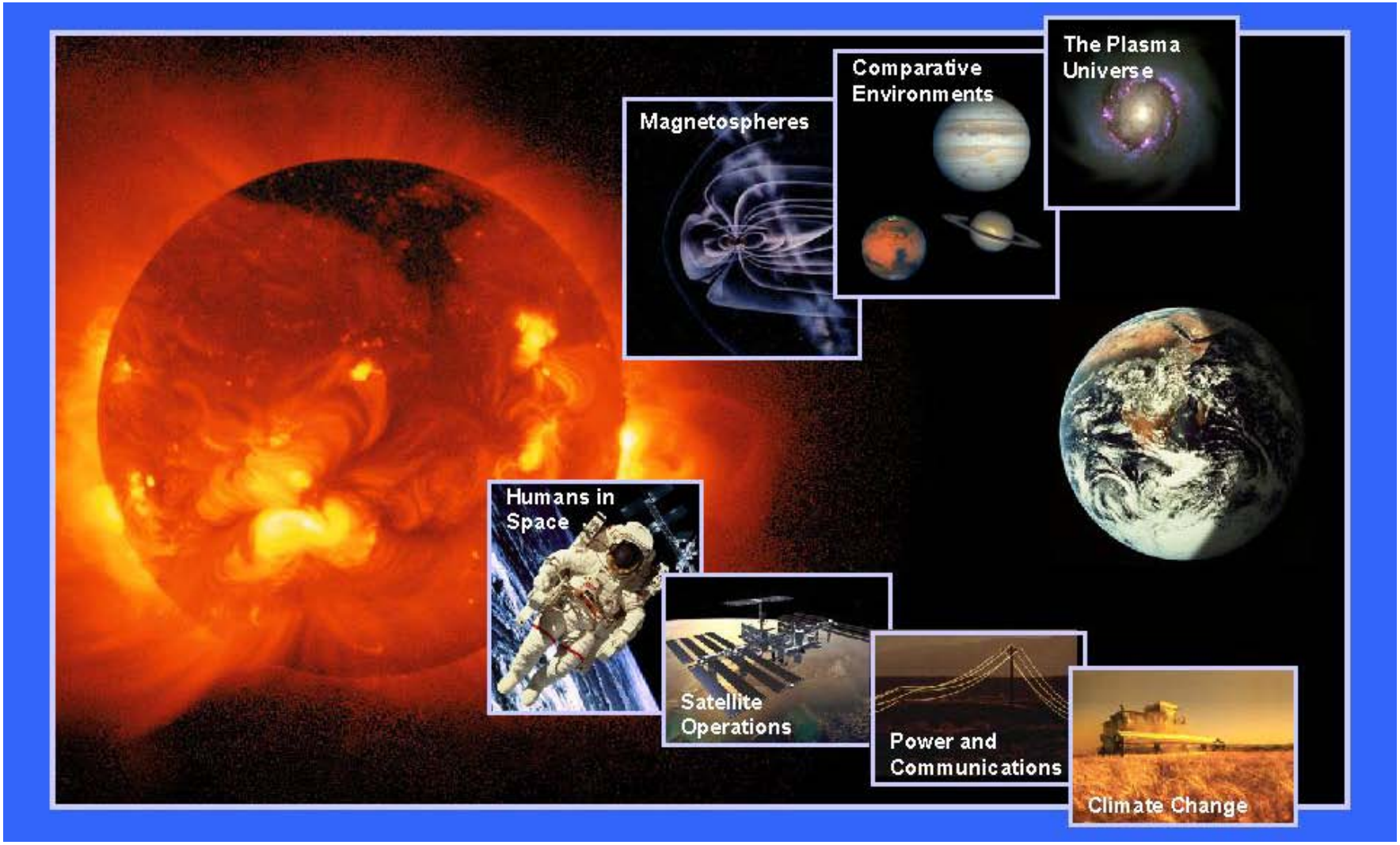
Understanding Sun-Earth Connections

Heliophysics Summer School - 2010



"Conversation about the weather is the last refuge of the unimaginative."

-Oscar Wilde

"Don't knock the weather; nine-tenths of the people couldn't start a conversation if it didn't change once in a while."

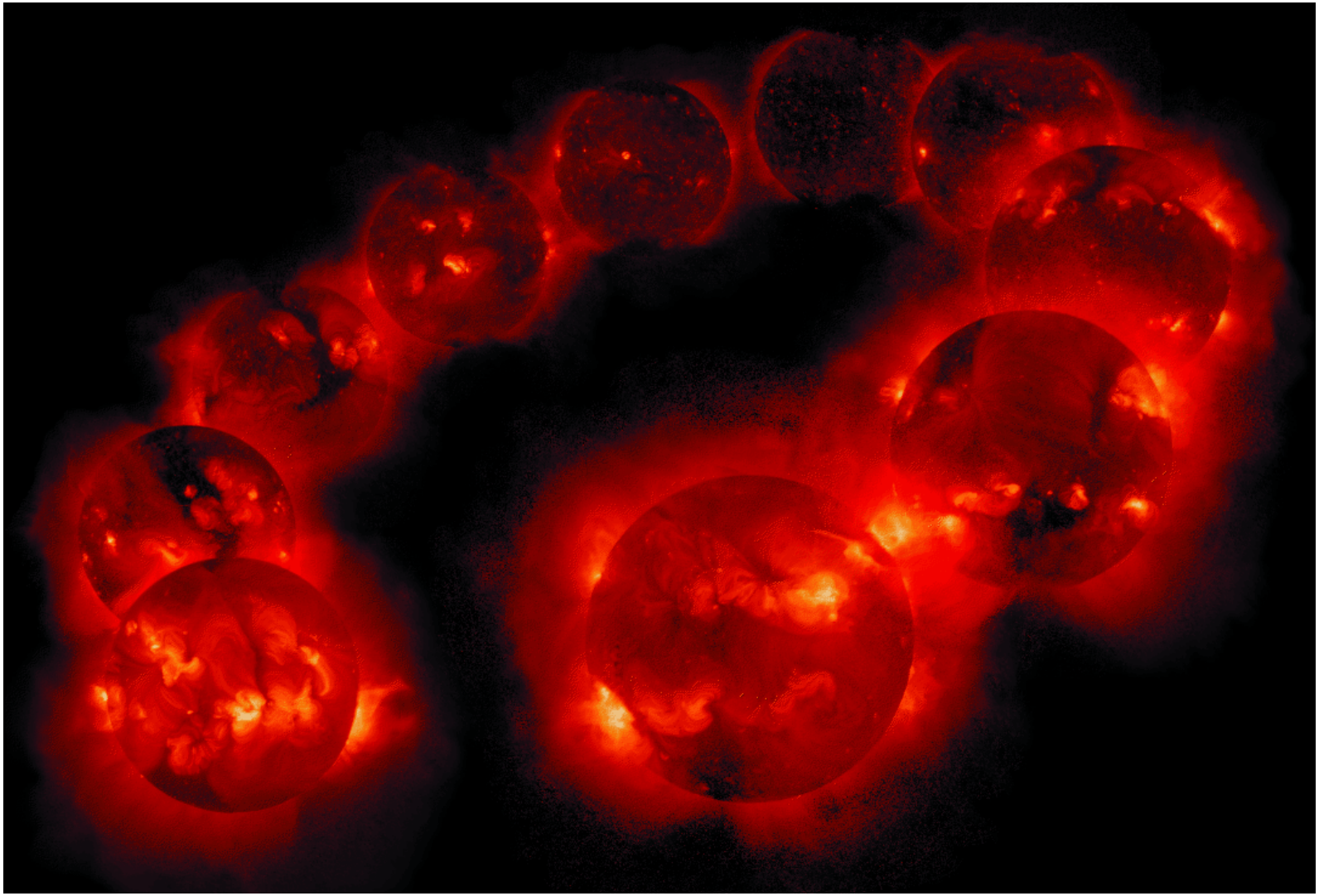
-Kin Hubbard

"Space Weather" refers to conditions on the sun and in the solar wind, magnetosphere, ionosphere, and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and endanger human life and health. Adverse conditions in the space environment can cause disruption of satellite operations, communications, navigation, and electronic power grids, leading to a panoply of socio-economic losses.

National Space Weather Program
Strategic Plan (March 1995)

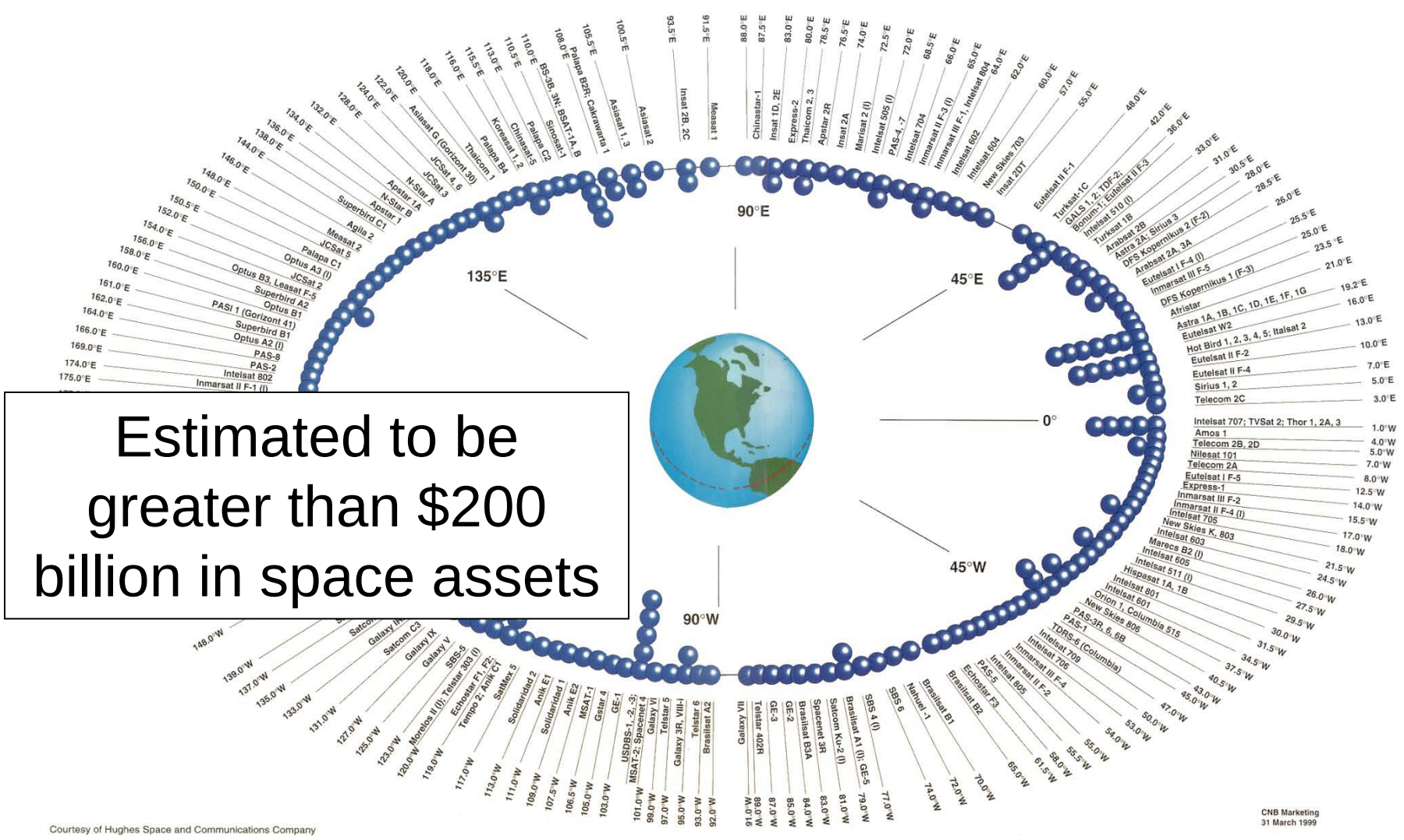

TWENTY-FIVE CENTS
MAY 4, 1959
TIME
E WEEKLY NEWSMAGAZINE
SPACE and the RADIATION BELT
PHYSICIST
JAMES VAN ALLEN
$7.00 A YEAR
VOL. LXXIII NO. 18

Yohkoh Soft X-rays: The 11-Year Solar Activity Cycle



Civilian Spacecraft at Geostationary Orbit

Heliophysics Summer School - 2010

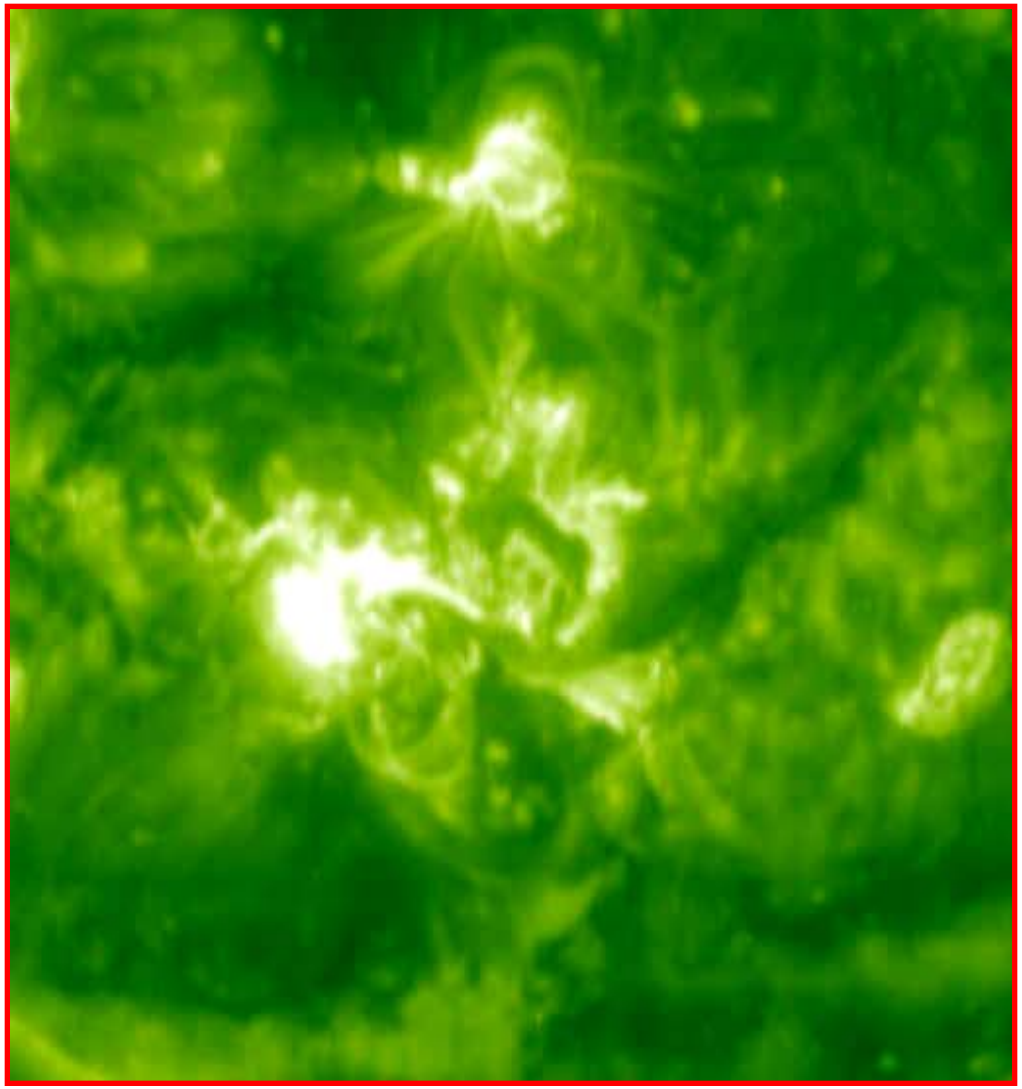


Estimated to be greater than $200 billion in space assets

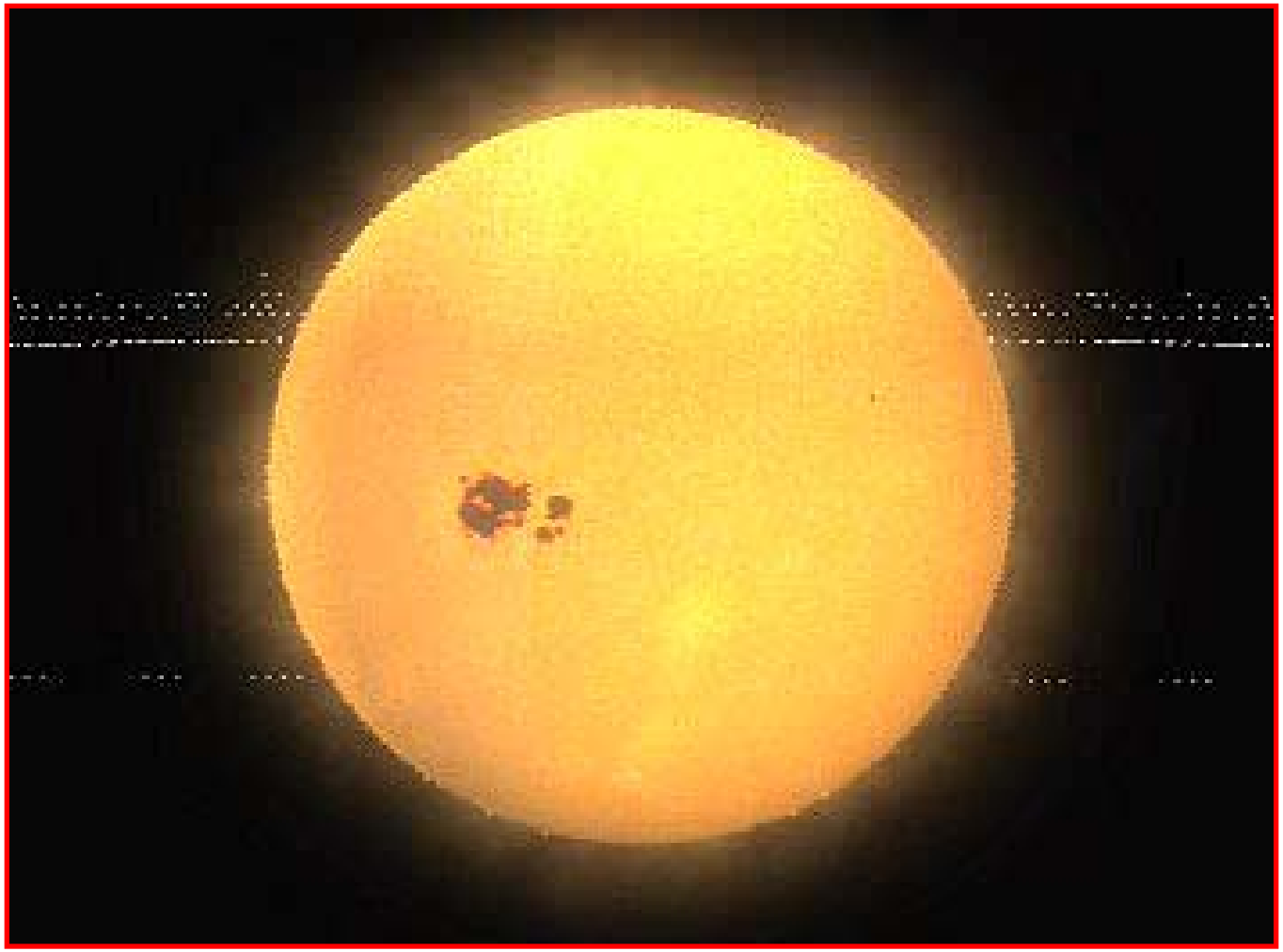
Coronal Mass Ejection - Earth Impact

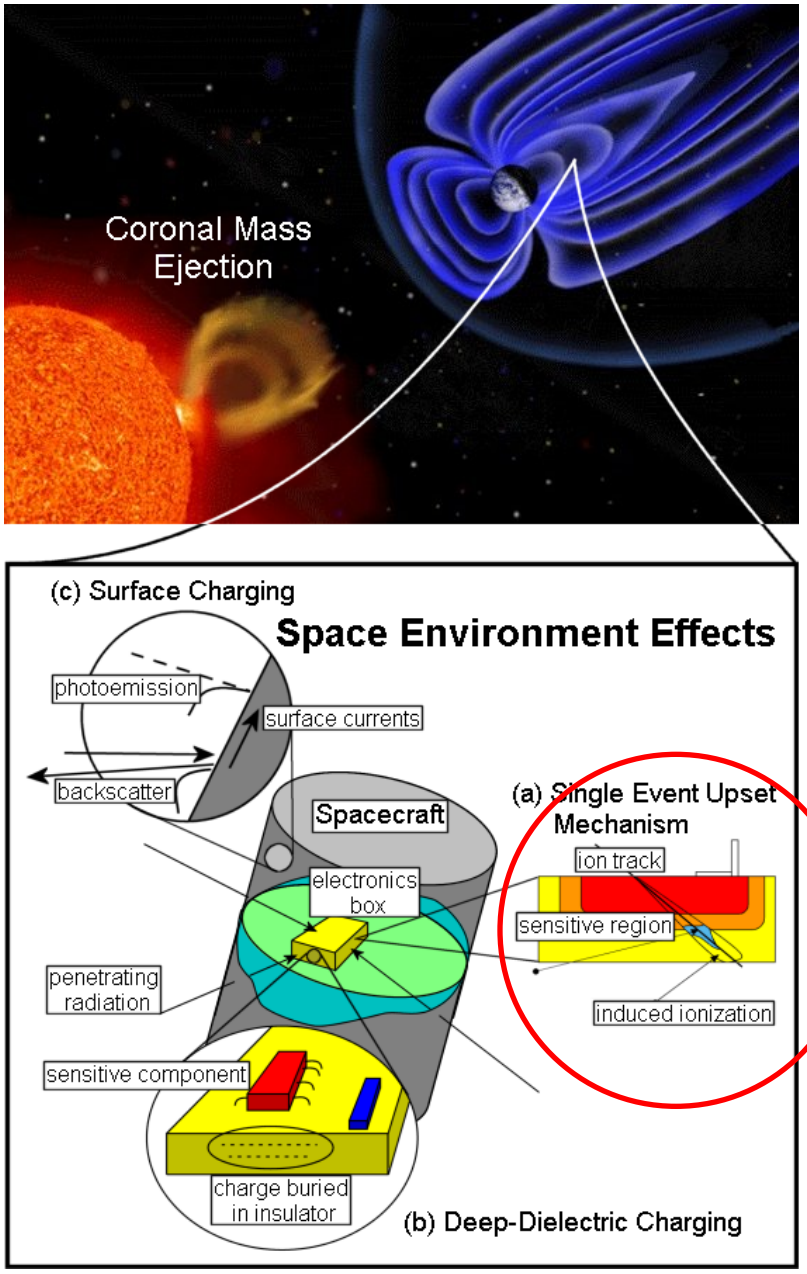
Courtesy of NASA

SOHO: Images of the Sun—October 2003



The Halloween Storms in the Heliosphere

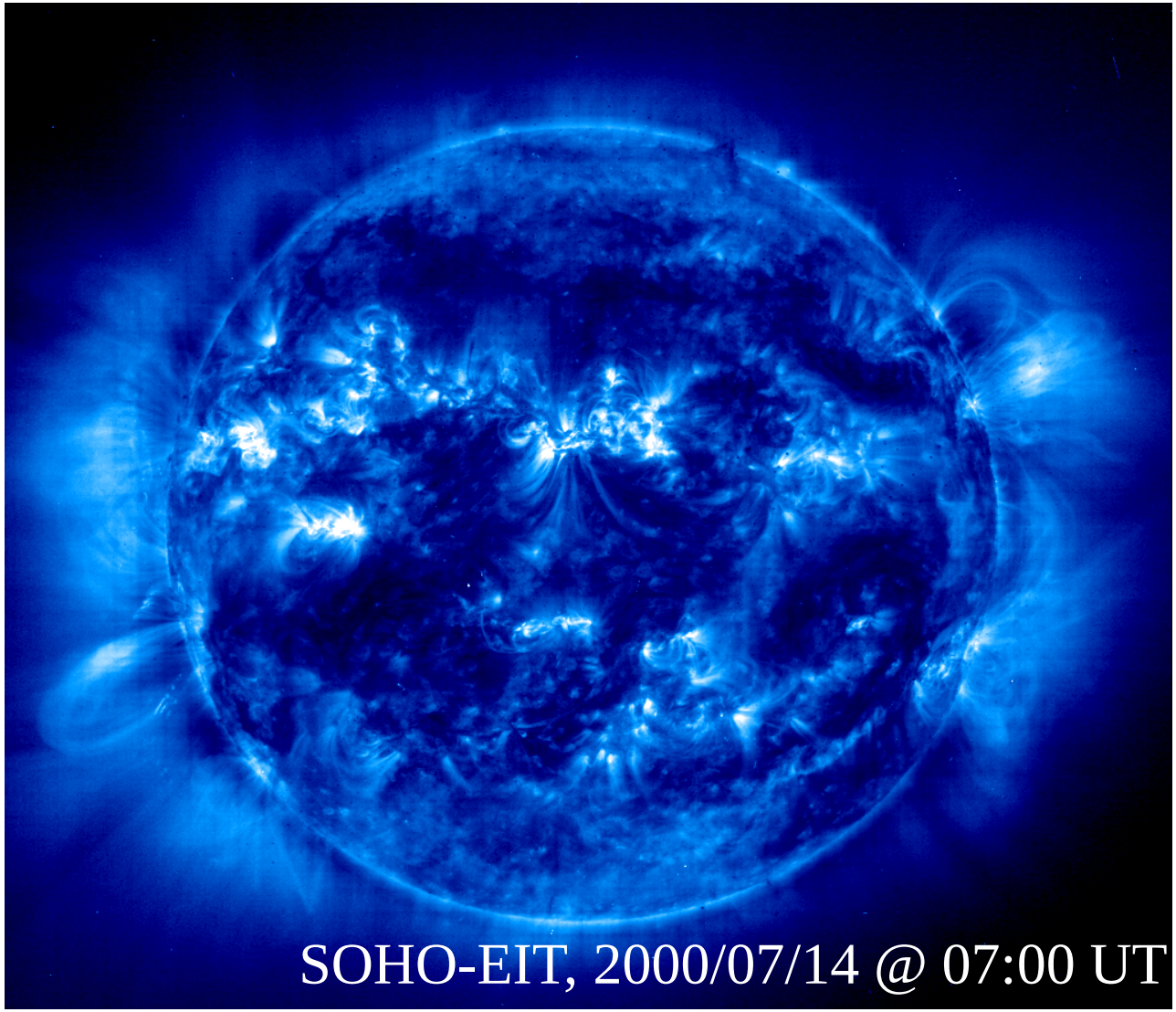




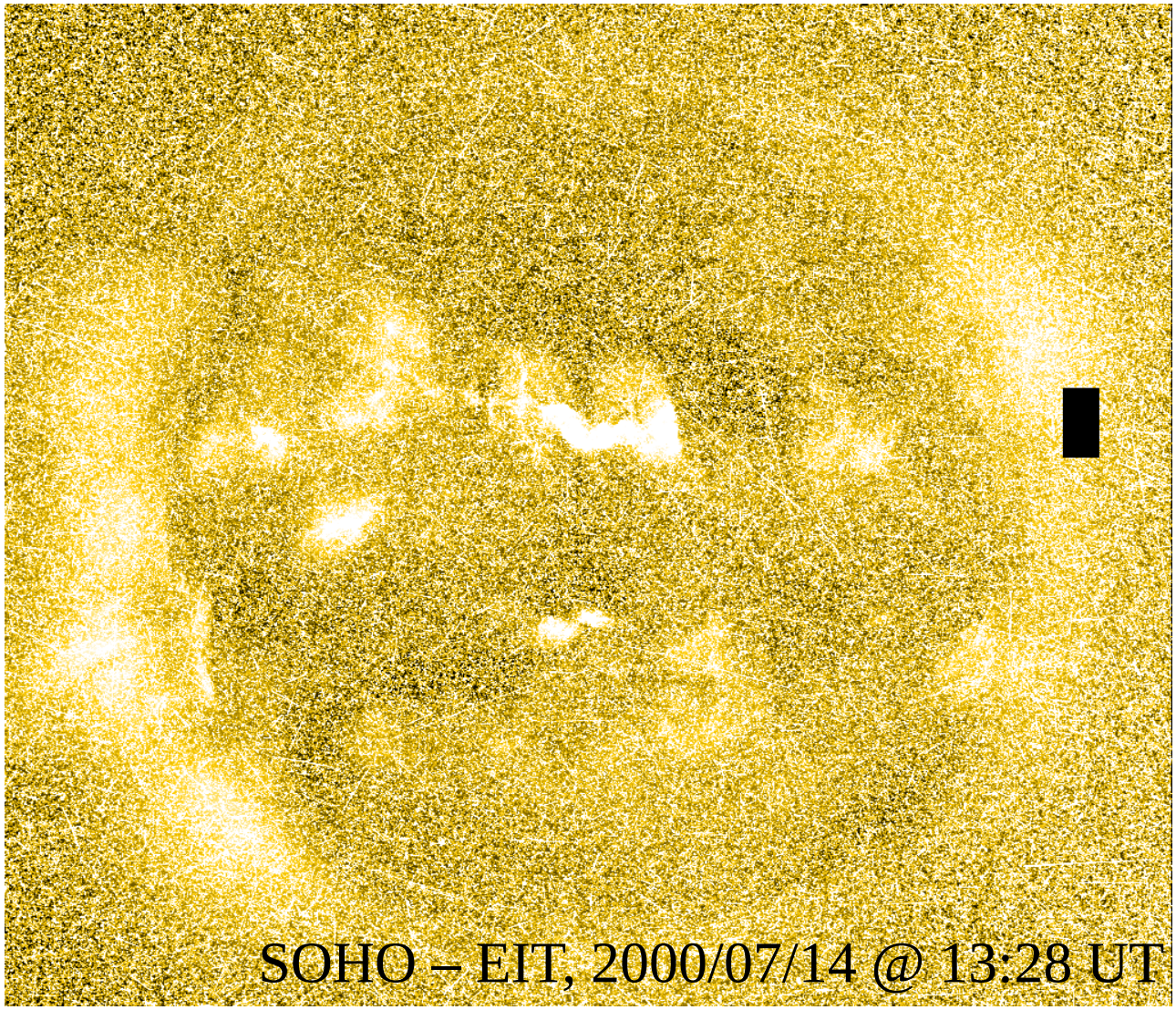
High-Energy Ion Effects

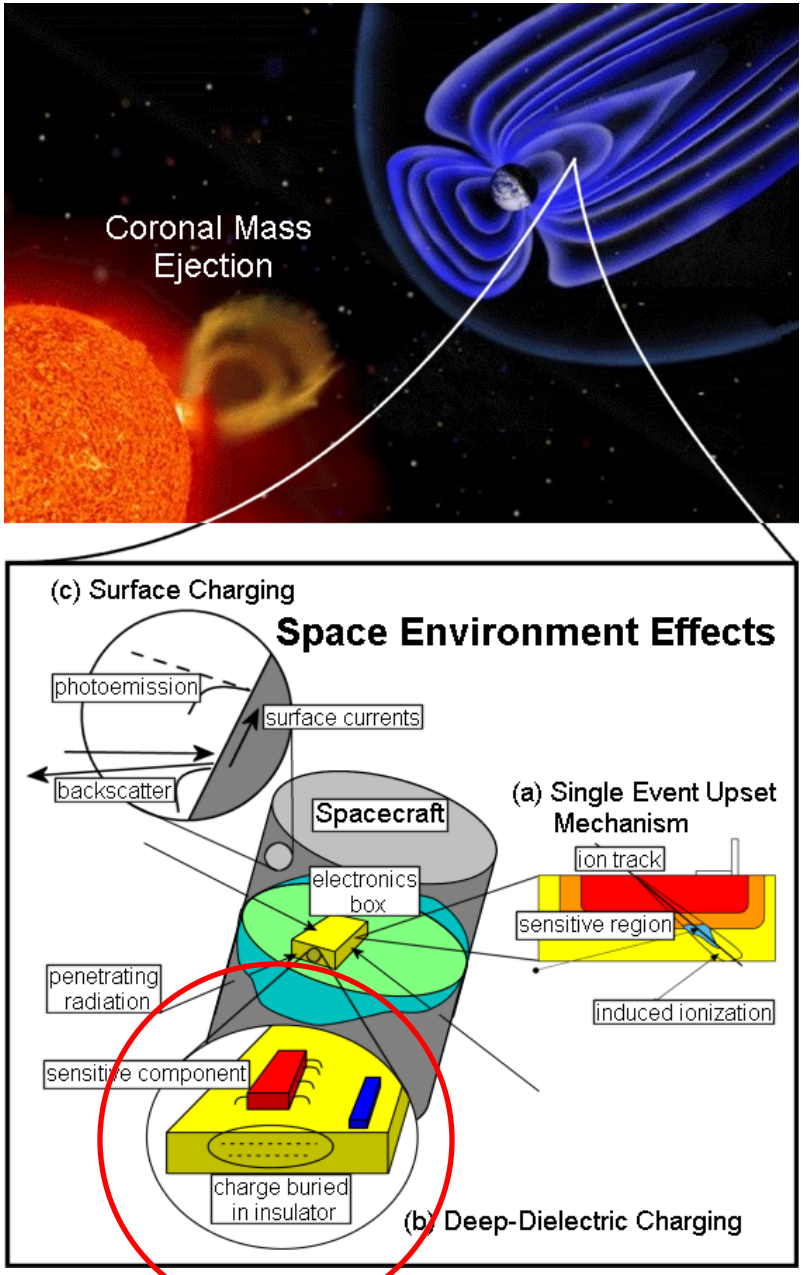
D.N. Baker "How to Cope with Space Weather," *Science*, *297*, 1486, 2002

The Active Sun: July 2000



Background Due to Solar Energetic Particles

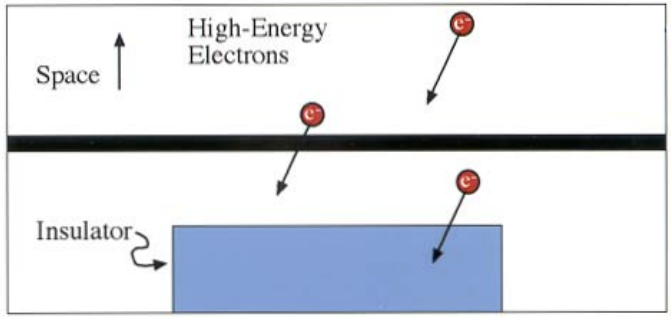




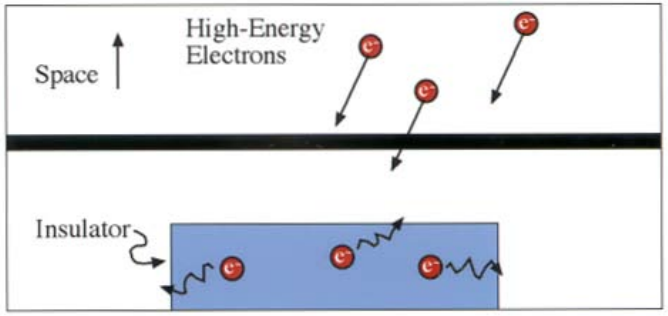
High-Energy Electrons

Electron (left) and Proton (right) Radiation Belt Models

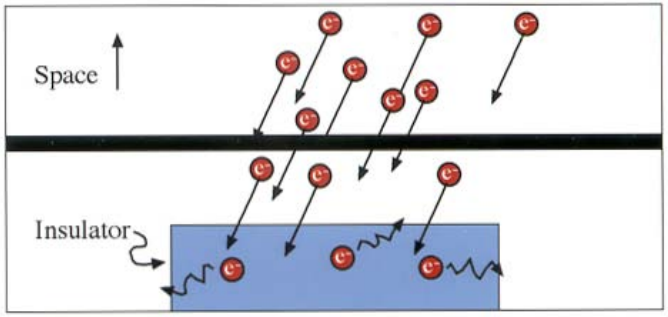
High-Energy Electrons: Deep-Dielectric Charging



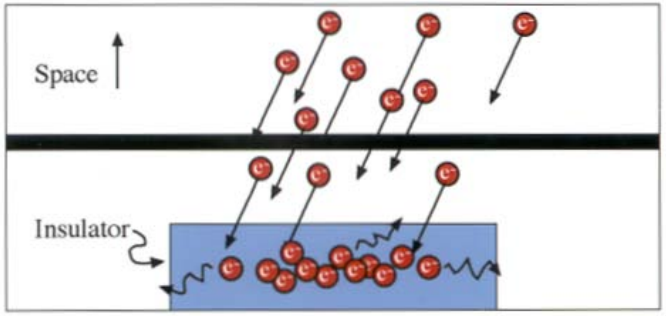
1. Electrons bury themselves in the insulator



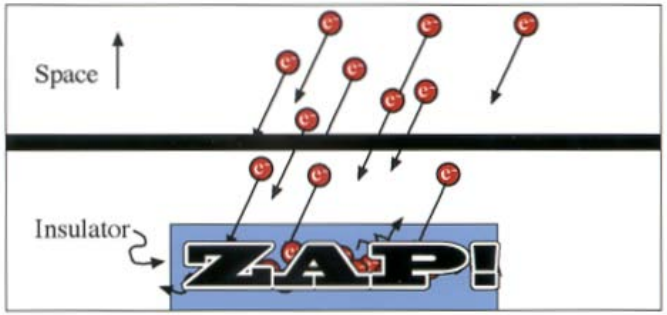
2. Electrons slowly leak out of the insulator



3. Influx of electrons increases to levels higher than the leakage rate



4. Electrons build up faster than they leak off

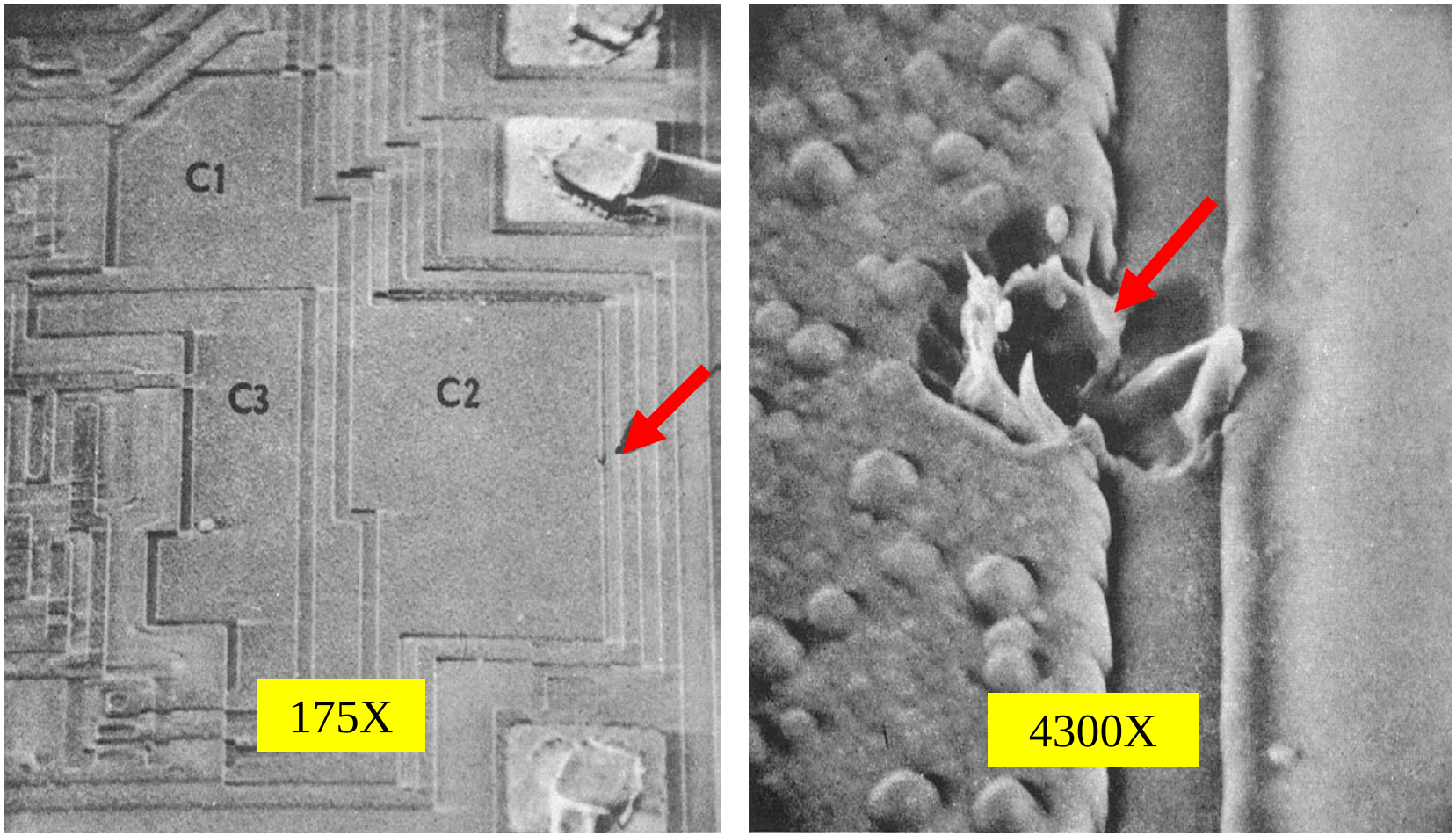


5. Discharge (electrical spark) that damages or destroys the material

Electrostatic Discharge (ESD)

- Definition:
  - A transfer of electrostatic charge between bodies at different electrostatic potentials caused by direct contact or induced by an electrostatic field.

ESD Damage

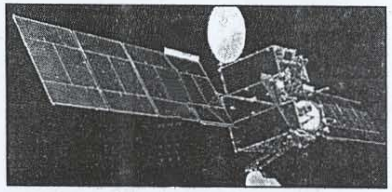


HA-2700 surface damage in the C2 MOS capacitor
(Courtesy of JPL)

The Hamilton Spectator

Established 1846 • Mon-Fri 47¢ + 3¢ GST

P-ANIK!



High-tech chaos as satellites spin out of control

Plug pulled on phones, TV, radio, papers

OTTAWA — Telesat Canada was facing some tough questions today as it tries to explain how its two main communication satellites tumbled out of control, interrupting TV, radio, newspaper and telephone signals across the country.

After struggling for more than eight hours to bring the wobbly Anik E-1 under control, Telesat technicians thought they had the problem licked late yesterday.

The were only half right.

Shortly after 9 p.m. EST, as Anik E-1 settled back into position, Telesat's primary broadcasting satellite, Anik E-2, also got a bad case of the shakes.

CBC Newsworld and other national specialty cable channels, including MuchMusic, TSN, Vision and the Weather Channel, were knocked off the air. Partial service, with signals carried by fibre-optic cable, was later restored in some major centres, including Toronto.

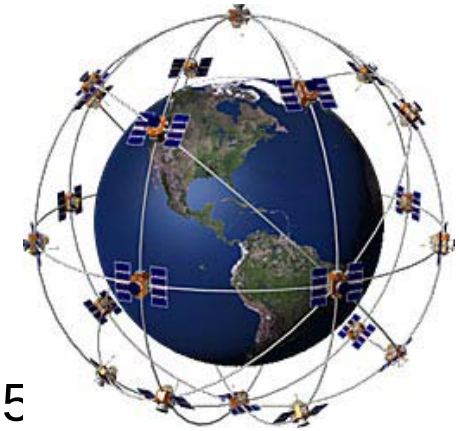
In Hamilton local cable companies and police communications were unaffected. The Mt. Hope weather office had minor disruptions.

"We don't know how it was brought about," said Chris Frank, Telesat's director of public affairs.

GPS Growth

Global Positioning System used: In-vehicle navigation systems, railway control, highway traffic management, emergency response, commercial aviation, and much more…

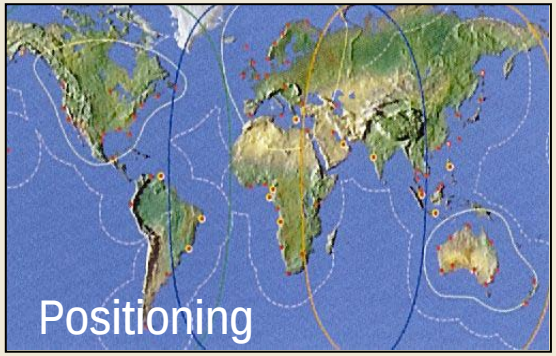
NAVSTAR - USA
GLONASS - Russia
Galileo - Europe

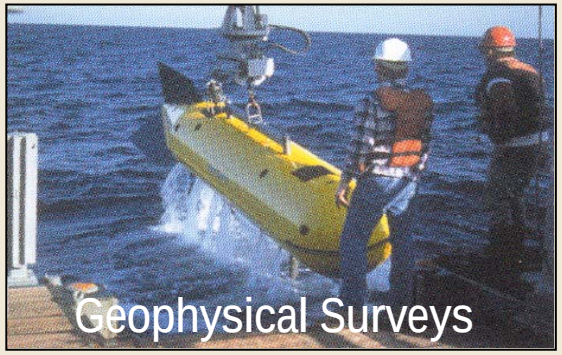


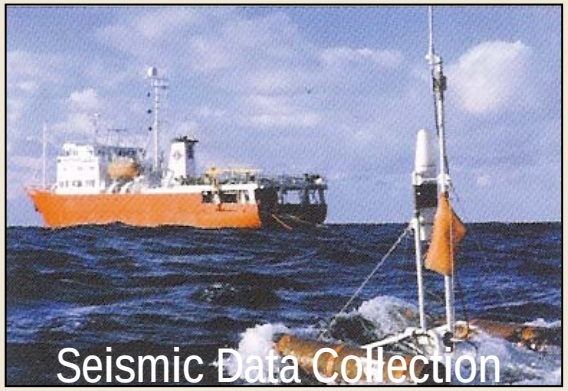
GPS Global Production Value—expected growth:
2003 - $13 billion
2008 - $21.5 billion
2017 - $757 billion
Industrial Technology Research Institute (ITRI) – Mar 2005

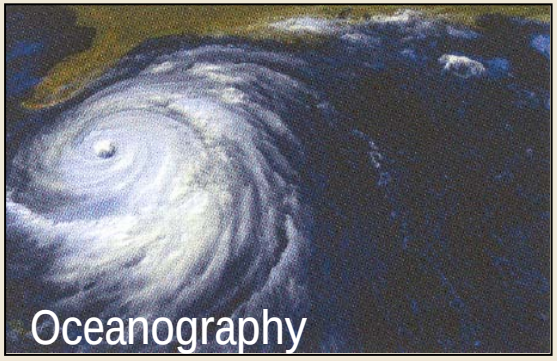
Space weather creates positioning errors larger than 50 meters
—A mid-latitude problem (where most users reside!)

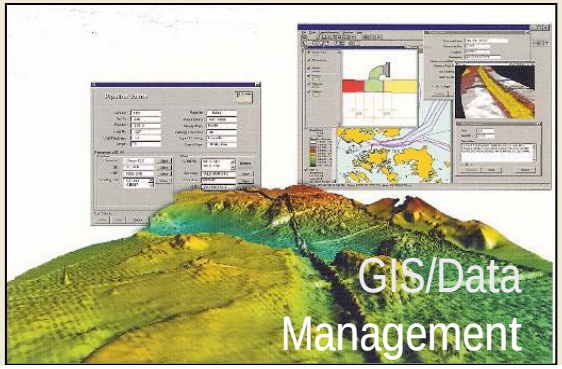
Business Lines







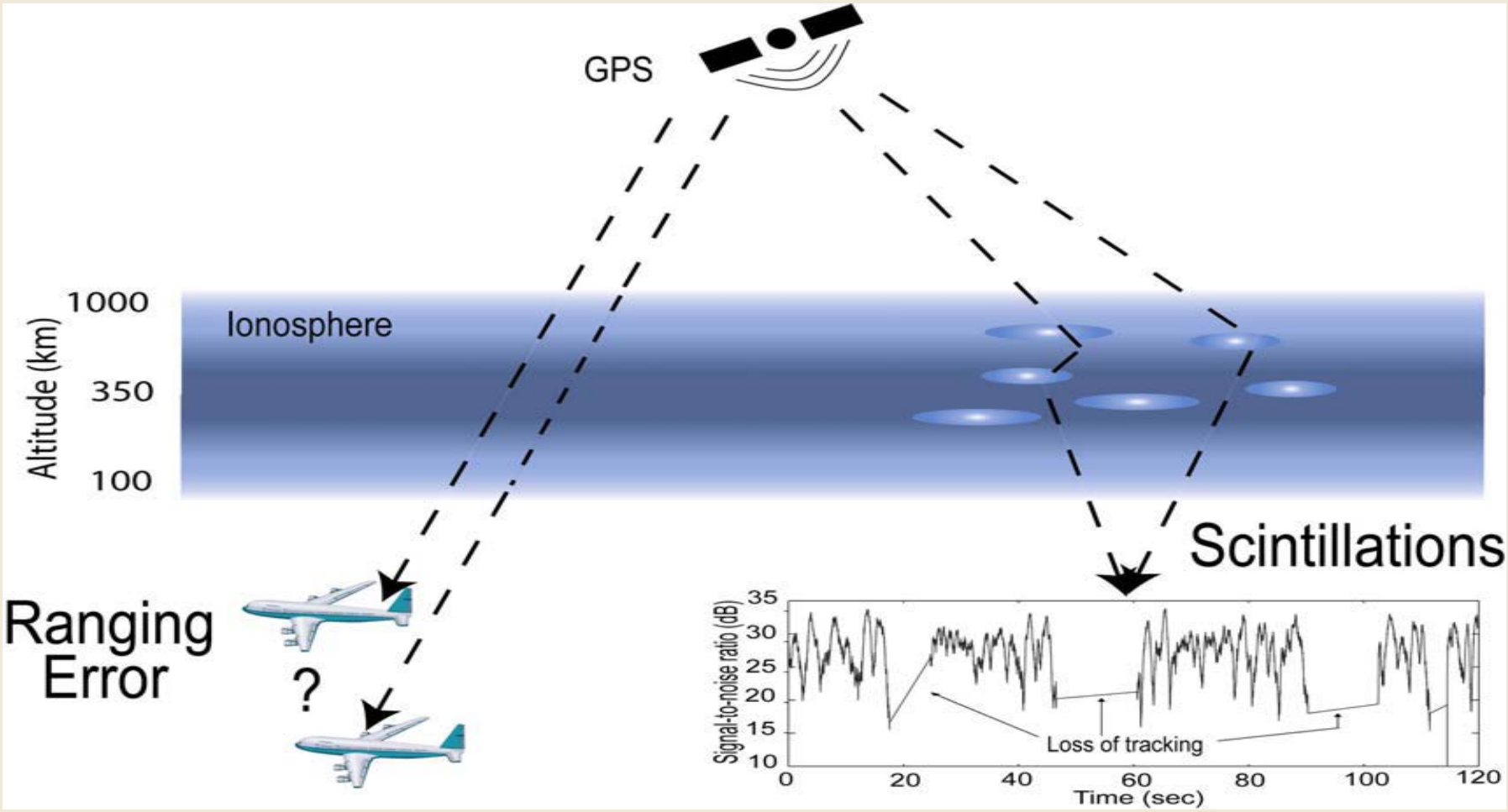





WAAS
Wide Area Augmentation System
GPS Satellites
Barrow
Kotzebue
Fairbanks
Bethel
Anchorage
Cold Bay
Juneau
Auburn
Billings
Salt Lake
Fremont
Palmdale
Longmont
Olathe
Albuquerque
Fort Worth
Houston
Winnipeg
Farmington
Iqaluit
Goose Bay
Gander
Oberlin
Aurora
Nashua
Ronkonkoma
Leesburg
Memphis
Hampton
Jacksonville
Miami
San Juan
Merida
San Jose Del Cabo
Puerto Vallarta
Mexico City
Tapachula
Honolulu
GEO Satellite
GEO Satellite
Wide-area Reference Station (WRS)
International WRS's
Wide-area Master Station (WMS)
Ground Uplink Station
as of 11/9/2007

GPS Ionospheric Ranging Errors and Scintillations

Tracking The GPS Signal Is Like Trying To See A 25 Watt Light Bulb 12,000 Miles Up



Ionospheric Range Delay result from normal signal propagation through the ionosphere.

Scintillations result from severe ionospheric signal scattering.

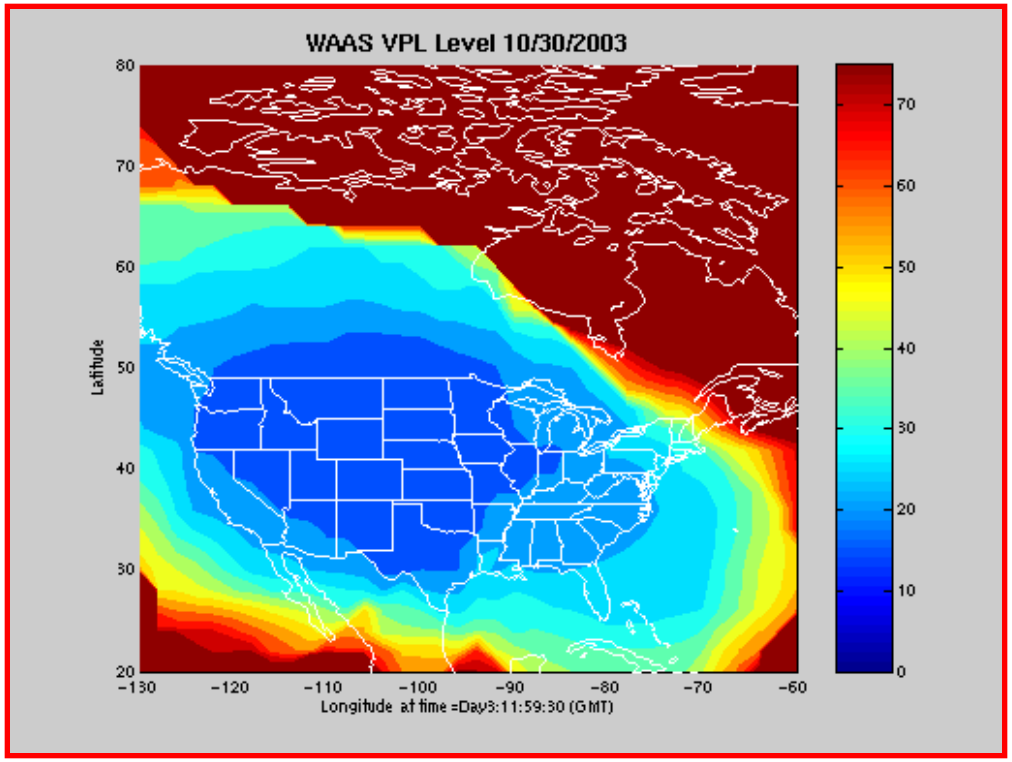
Amplitude Fading or signal to noise degradation are caused by solar radio bursts.

Graphic from Cornell University

Wide Area Augmentation System (Oct. 2003)

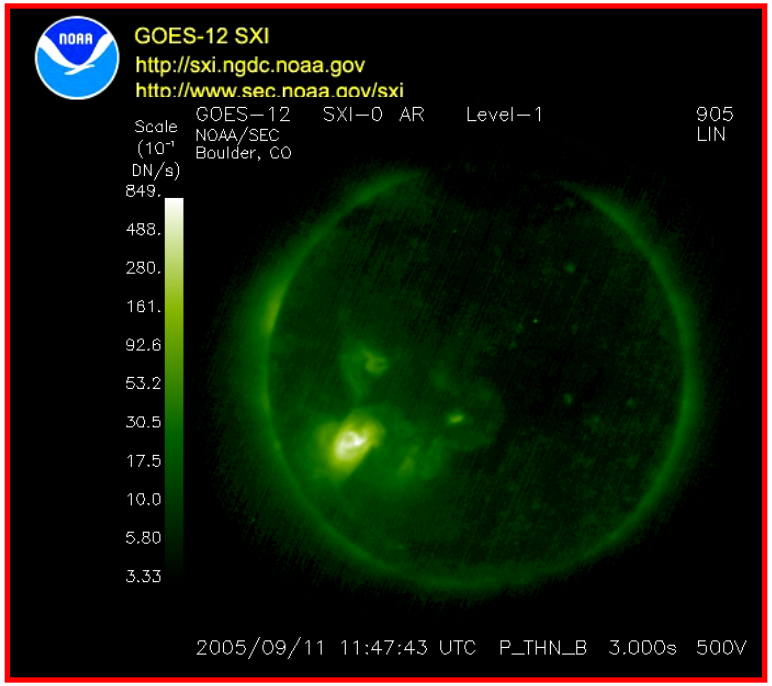
Ionosphere disturbances impact vertical error limits, defined by the FAA's Lateral Navigation/Vertical Navigation (LNAV/VNAV) specification to be no more that 50 meters.

Commercial aircraft unable to use WAAS for precision approaches.

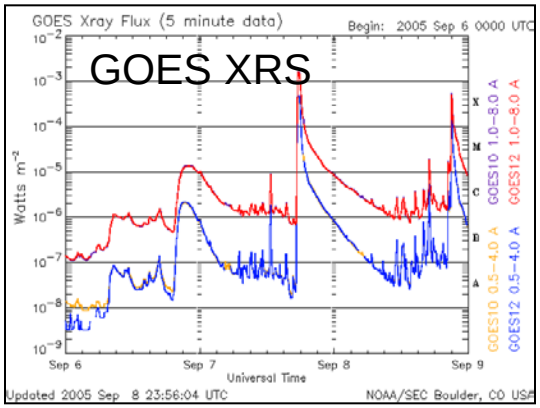


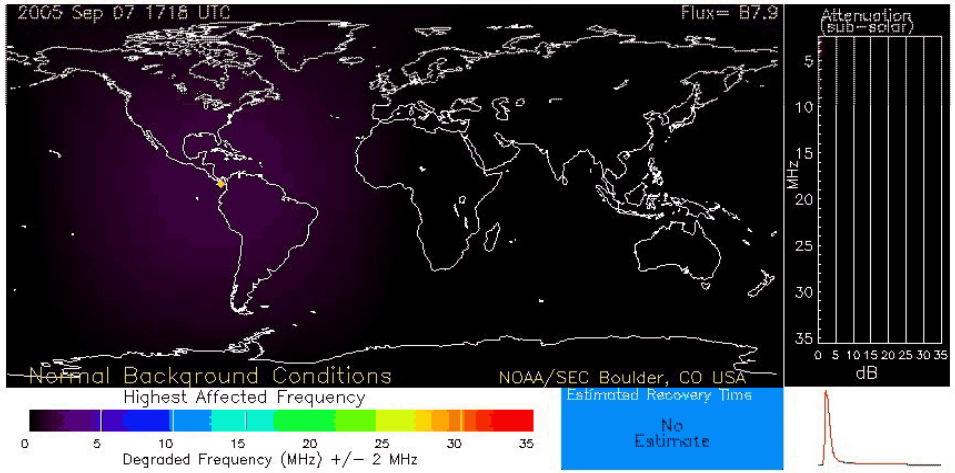
Airlines and Space Weather

Heliophysics Summer School - 2010



GOES SXI





Loss of High Frequency (HF) communications during a solar flare.
The night-side of the Earth is unaffected

Image from NASA SOHO Satellite

UAL POLAR ROUTES

WASHINGTON

CHICAGO

82 N

ABERI

DEVID

RAMEL

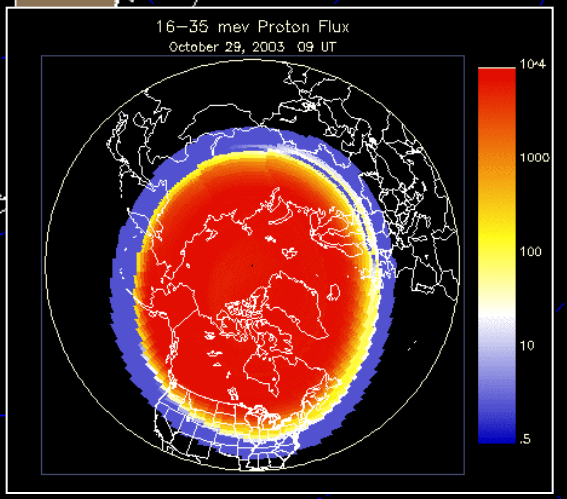
NIKIN

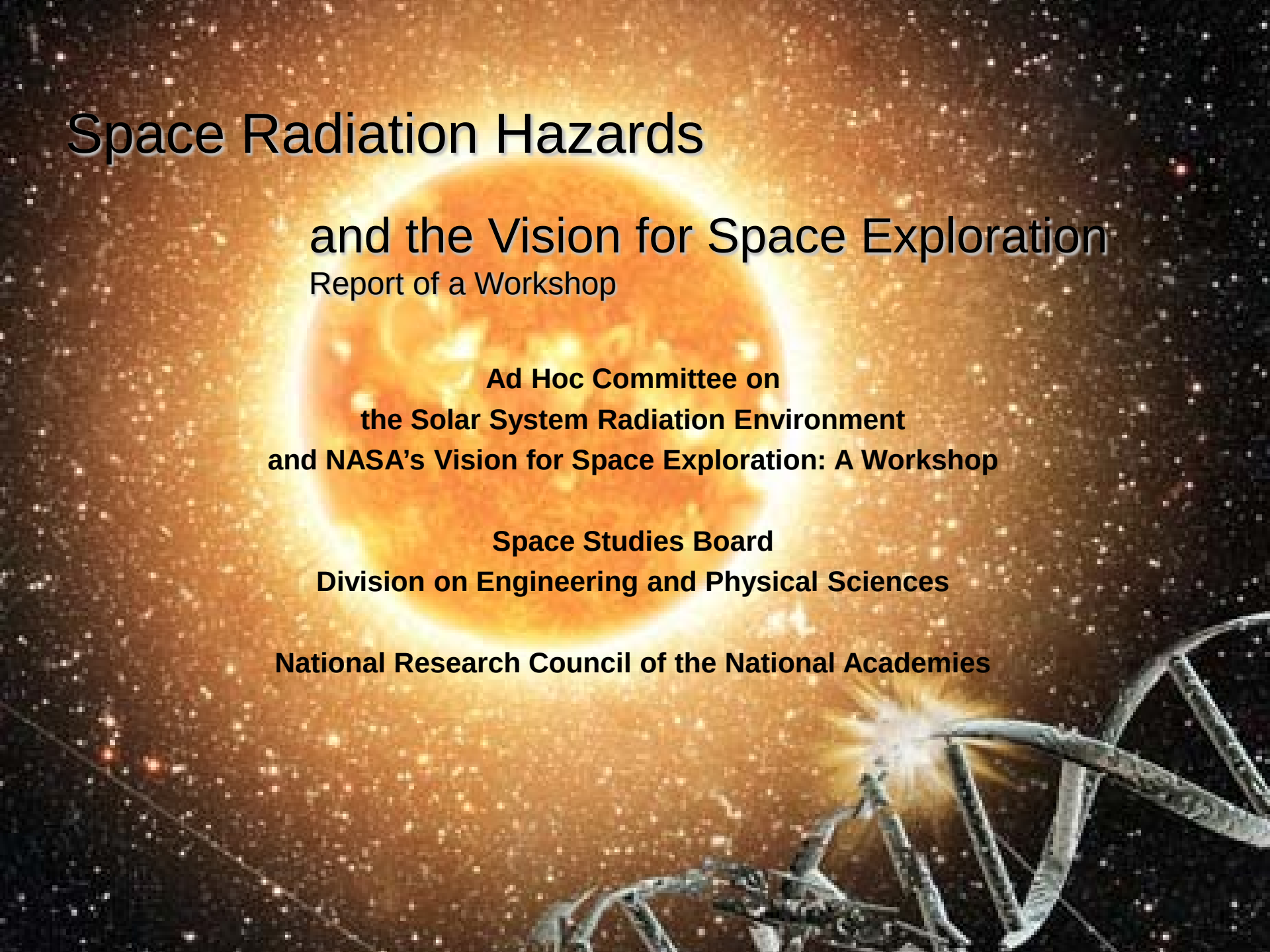
ORVIT

BEIJING

HONG KONG

SHANGHAI





Space Radiation Hazards

and the Vision for Space Exploration

Report of a Workshop

Ad Hoc Committee on

the Solar System Radiation Environment

and NASA's Vision for Space Exploration: A Workshop

Space Studies Board

Division on Engineering and Physical Sciences

National Research Council of the National Academies

Human Space Flight

- Shuttle missions and EVAs require particular attention. Note: *The EVA-1 hr briefing is the last opportunity to abort an EVA due to space weather. (>30 MeV events are primary concern)*

NASA SRAG will report to Mission Control when:

>K6 observed *(One 3-hr period after decay)*

>M5 observed

Protons (All >100 MeV events).

- Electron belt enhancements can delay or postpone an EVA.

ISS: 50 pfu at > 100 MeV - shutdown the robotic arm

100 pfu at > 100 MeV - alert Mission Control. The Flight Team will start to evaluate a plan to shutdown equipment to prevent damage to electronics.

200 pfu > 100 MeV - plan is implemented

Radiation Risks

- Carcinogenesis
  - Leukemia
  - Solid Cancers
  - Age/Gender Differences
- Degenerative Tissue Effects
  - Heart Disease
  - Cataracts
  - Respiratory Disease
  - Digestive Diseases
- Damage to the Central Nervous
  - Motor Skills
  - Behavior
  - Accelerated Aging
- Acute Risks
  - Death
  - Vomiting/Nausea

Potential Outcomes

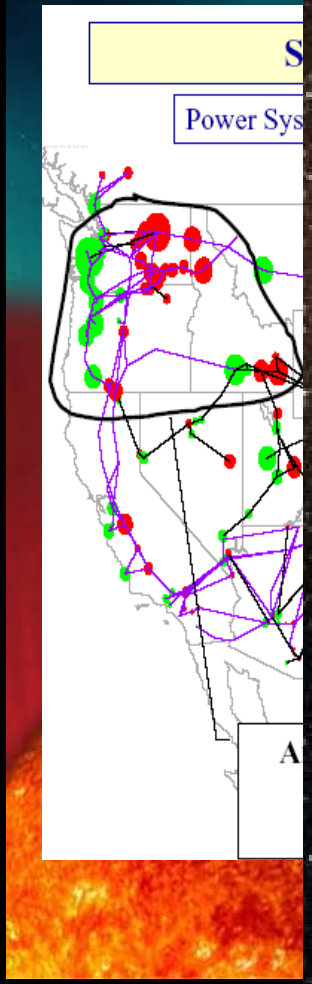
- Mortality: Reduced Lifespan
- Mortality: In-flight (Acute from SEP Events)
- Performance Degradation:
- Morbidity: Post-Flight

[Baker et al., ***NRC Space Radiation Report***, 2006]

Figure 1.2

Economic Impacts of Space Weather

- Airborne Survey Data Collection: $50,000 per day
- Marine Seismic Data Collection: $80,000-$200,000 per day
- Offshore Oil Rig Operation: $300,000-



Space Radiation Hazards and the Vision for Space Exploration

ystem

d growth:

2008 - $21.5 billion

2017 - $757 billion

Industrial Technology Research Institute (ITRI) – Mar 2005

Task

- An ad hoc committee of the Space Studies Board (SSB) of the National Academies was charged to convene a workshop to assess the current and future ability to manage space weather events and their societal and economic impacts.
  - What are the socioeconomic consequences of severe space weather events?
  - How likely are very intense space weather storms and what might be the consequences of such events?
  - Are there specific ground- or space-based sensors or other approaches that might mitigate or avoid the effects of future severe space weather events?

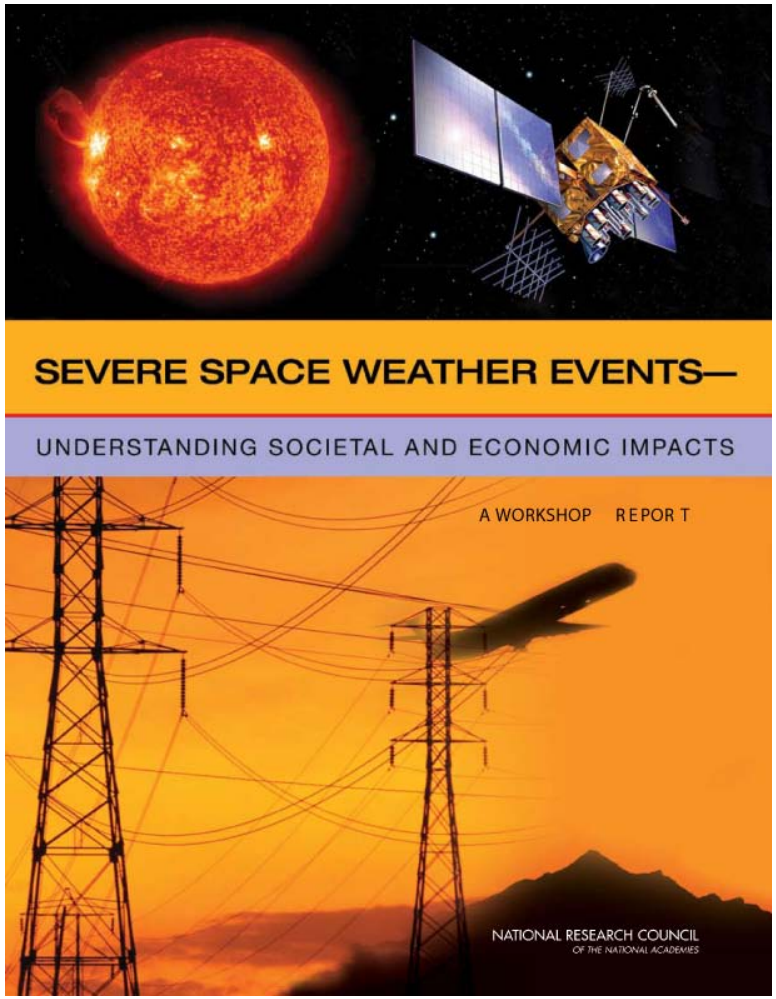
Committee on the Societal and Economic Impacts of Severe Space Weather Events

- DANIEL N. BAKER, University of Colorado at Boulder, Chair
- ROBERTA BALSTAD, Center for International Earth Science Information Network, Columbia University
- J. MICHAEL BODEAU, Northrop Grumman Space Technology
- EUGENE CAMERON, United Airlines, Inc.
- JOSEPH F. FENNELL, Aerospace Corporation
- GENENE M. FISHER, American Meteorological Society
- KEVIN F. FORBES, Catholic University of America
- PAUL M. KINTNER, Cornell University
- LOUIS G. LEFFLER, North American Electric Reliability Council (retired)
- WILLIAM S. LEWIS, Southwest Research Institute
- JOSEPH B. REAGAN Lockheed Missiles and Space Company, Inc. (retired)
- ARTHUR A. SMALL III, Pennsylvania State University
- THOMAS A. STANSELL, Stansell Consulting
- LEONARD STRACHAN, JR., Smithsonian Astrophysical Observatory

- Staff
- SANDRA J. GRAHAM, Study Director
- THERESA M. FISHER, Program Associate
- VICTORIA SWISHER, Research Associate
- CATHERINE A. GRUBER, Assistant Editor

The Societal and Economic Impacts of Severe Space Weather Events: A Workshop

- May 22-23, 2008 in DC
- Approximately 80 attendees from academia, industry, government, and industry associations
  - Association reps aggregated data and helped avoid concerns about proprietary or competition-sensitive data
- Analyses in specific areas; e.g., GPS, power industry, aviation, military systems, human and robotic exploration beyond low-Earth orbit
- Econometric analysis of value of improved SpaceWx forecasts



[http://www.nap.edu/catalog.php?record_id=12507]

Anticipated Benefits

- Economic Impacts analysis would provide:
  - Better guidance for policy makers on investment in SWx systems
  - Better rationale for agency budgeting
  - Better understanding of “high-payoff” forecasts
  - Clearer guidance for future human exploration
  - Improved societal appreciation for SWx risks

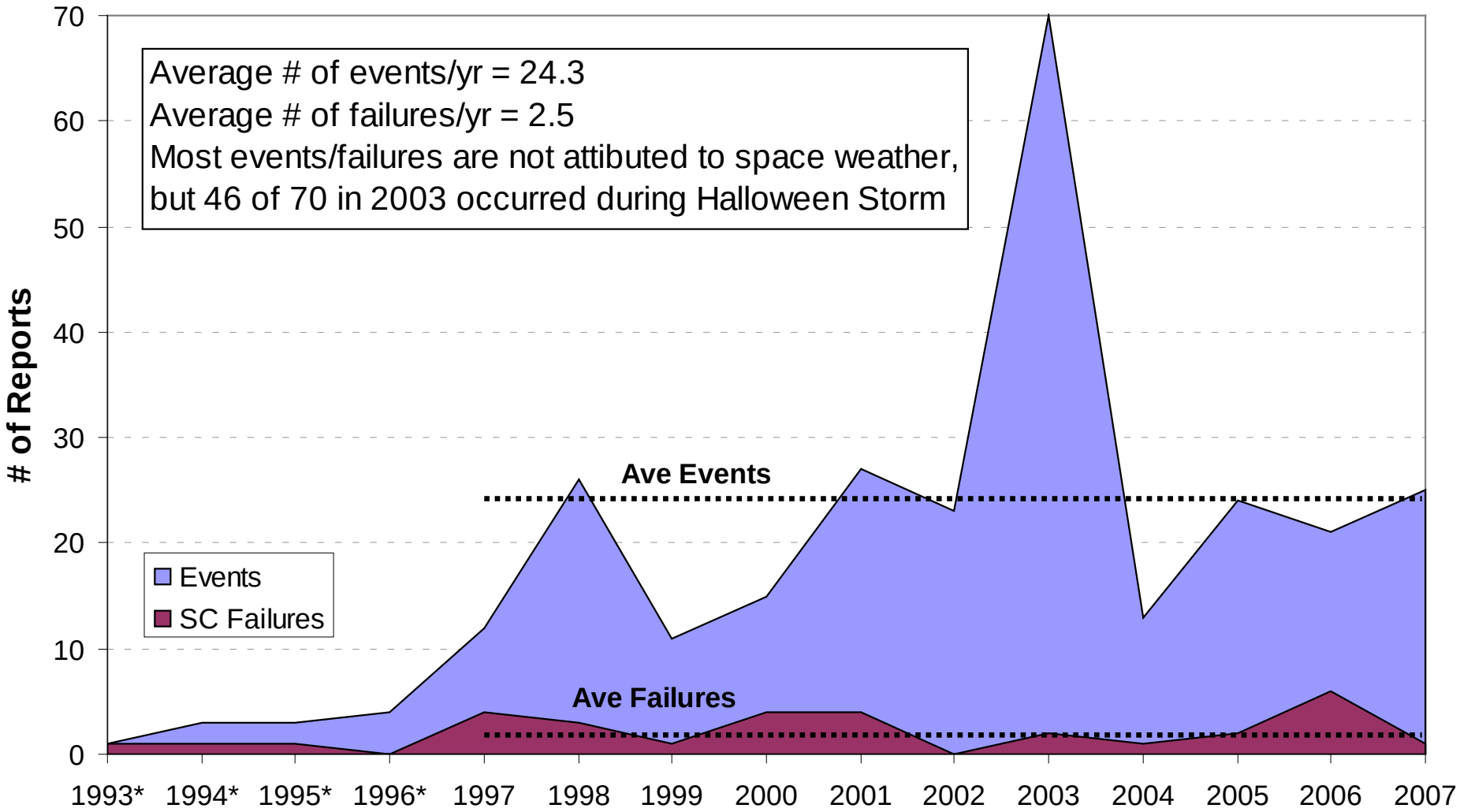
What Were Goals and Some Outcomes?

- Identify decisions that can be improved using a reliable forecast
- Differences with and without forecast (the expected value of a forecast)
- When best design decisions are made
- Economic impact of events
  - Repair damaged S/C: $50-70M
  - Replace commercial S/C: $250-300M
  - Cost of major power blackout: $4-10B
  - Extreme storm (a la 1859): $1-2 Trillion

Impacts of Space Weather

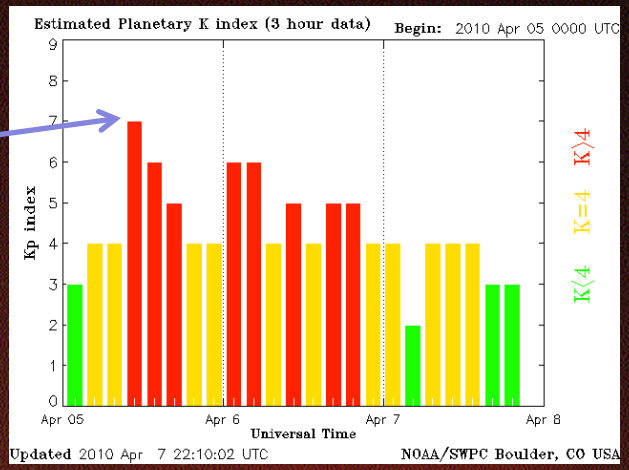
- Industry-specific Space Weather Impacts
  - Electric power, spacecraft, aviation, and GPS-based positioning industries can be adversely affected by extreme space weather
  - January 2005: 26 United Airlines flights diverted to nonpolar or less-than-optimum polar routes during several days of disturbed space weather
  - October-November 2003: FAA's recently implemented GPS-based Wide Area Augmentation System disabled for 30 hours
  - January 1994: Outage of two Canadian telecommunications satellite. Recovery took 6 months and cost $50 million to $70 million.

Spacecraft Anomalies and Failures



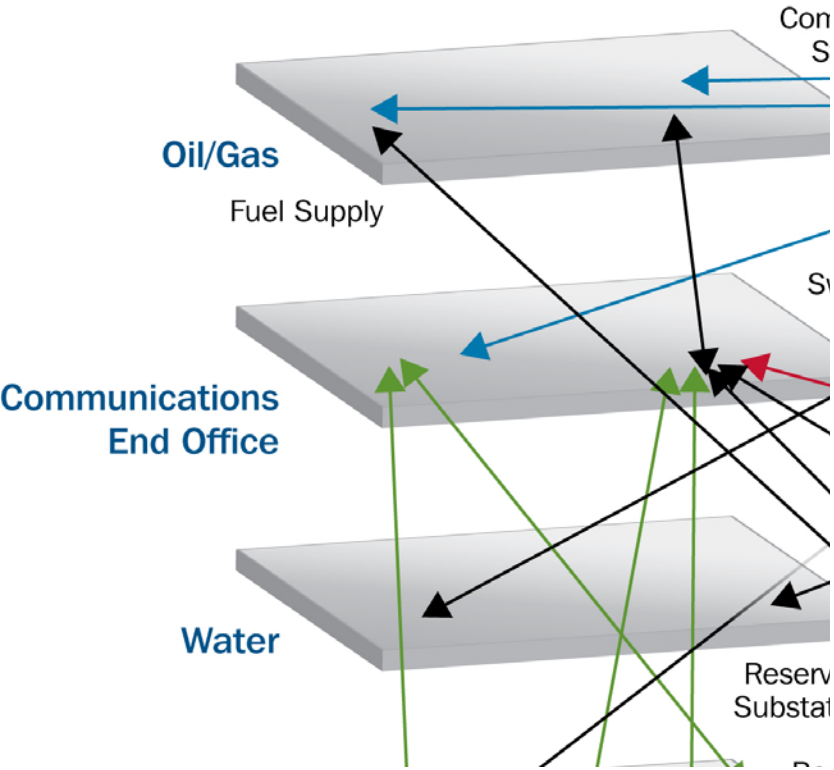
April 2010 – first significant space weather storm of new solar cycle.

- G3 geomagnetic storm observed on April 5, 2010



- April storm suspected in failure of Galaxy-15 satellite
  - No backup for FAA WAAS transponder

The Interdependencies of Society

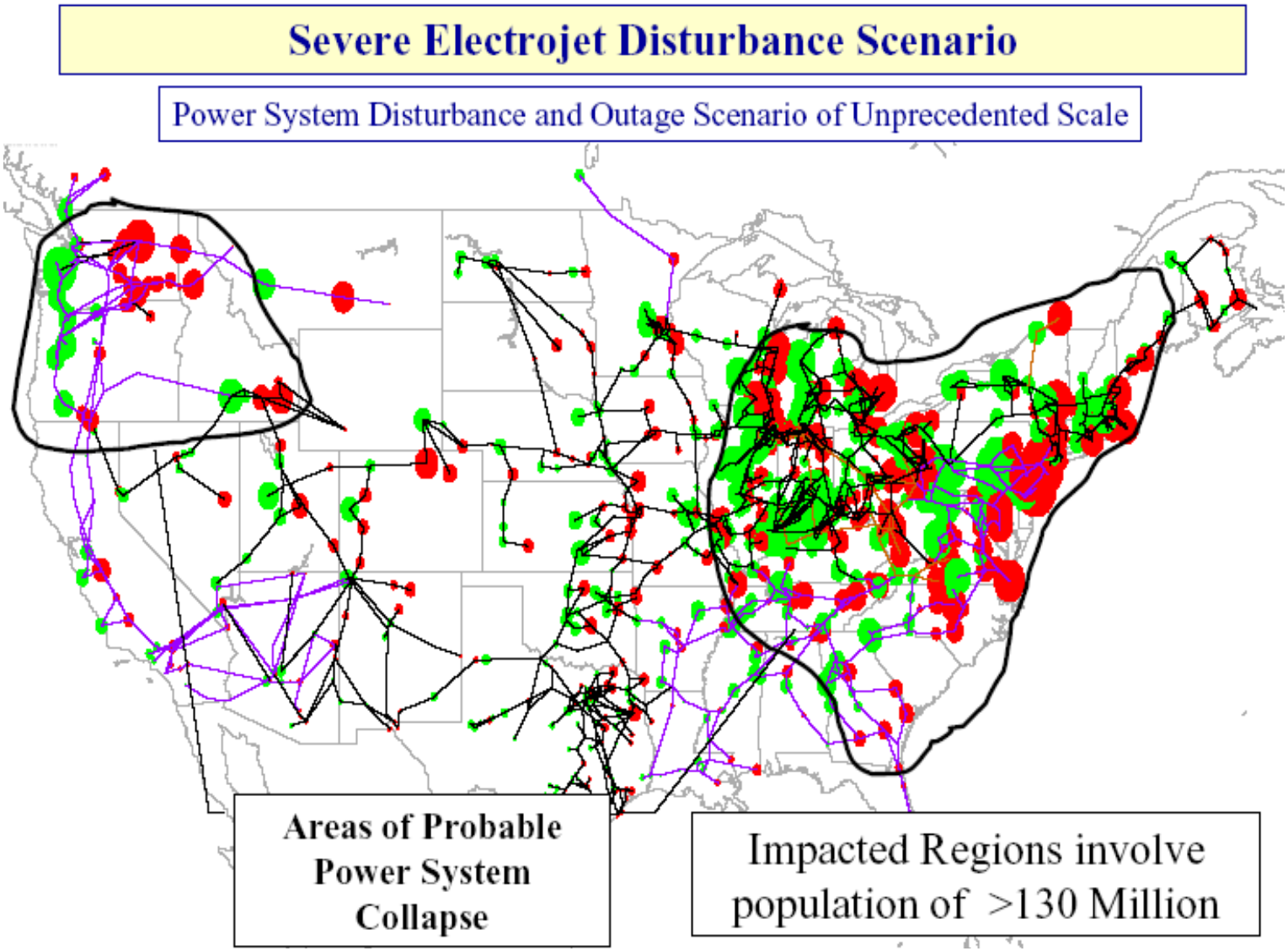


Electrical Power Grid…

The grid is becoming increasingly vulnerable to space weather events *Future Directions in Satellite-derived Weather and Climate Information for the Electric Energy Industry – Workshop Report Jun 2004*

"…blackouts could exceed even that of the very large blackout that occurred in August 14, 2003. And there is no part of the U.S. power grid that is immune to this… we could impact over 100 million population in the worst case scenario." John Kappenman - before U.S. House Subcommittee on Environment, Technology & Standards Subcommittee Hearing on *"What is Space Weather and Who Should Forecast It?"*

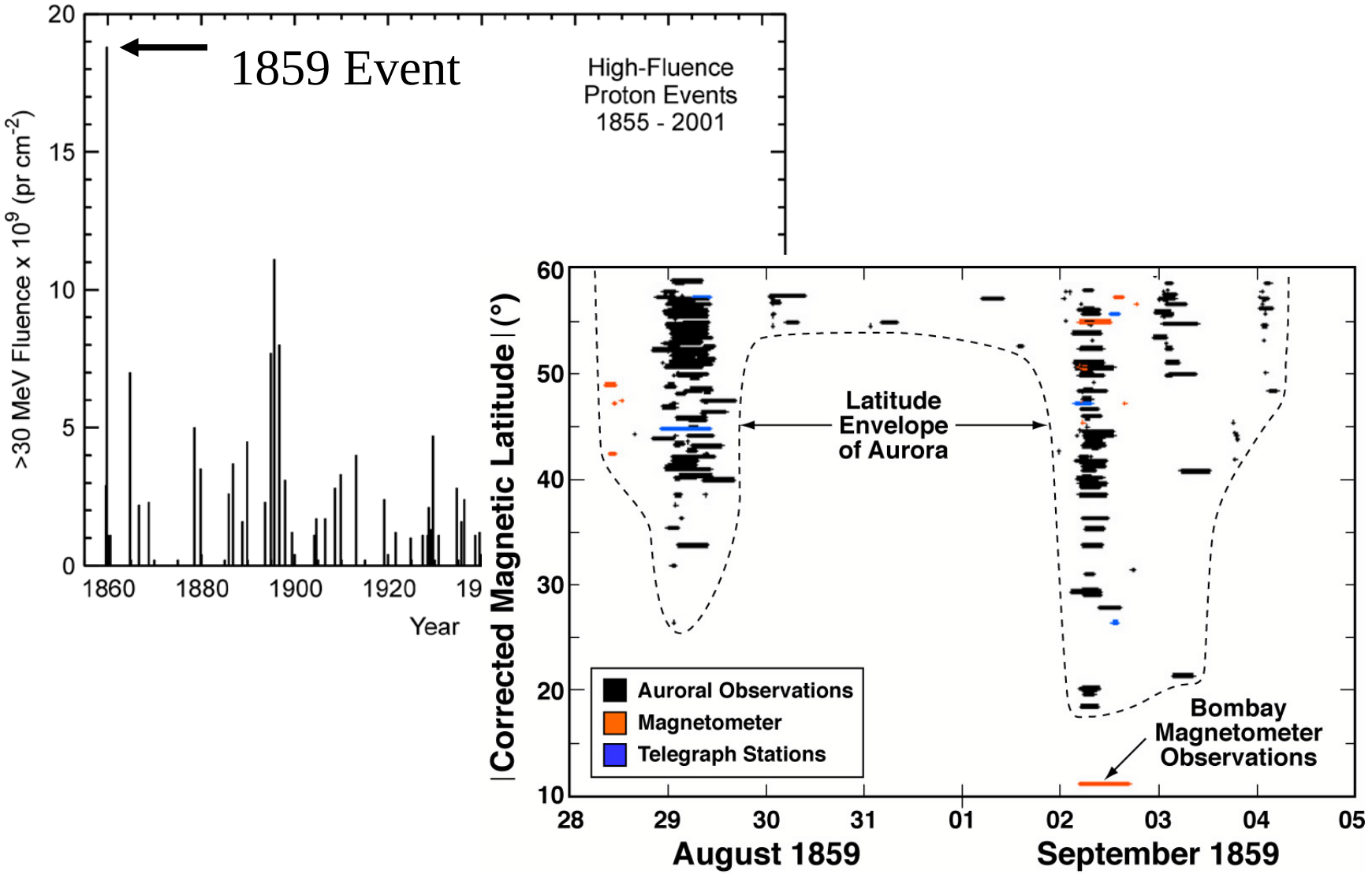
Regional Power Grid Disruptions



Impacts of Space Weather

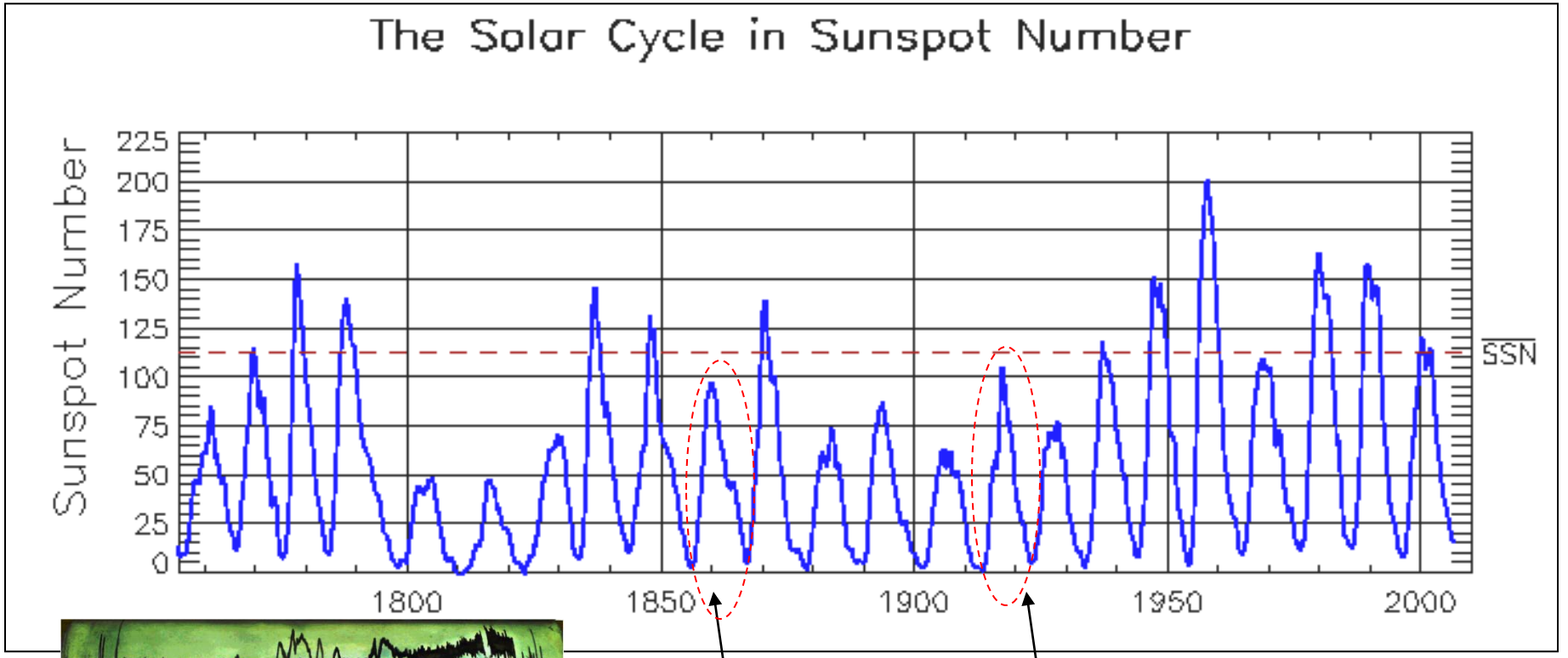
- Collateral Impacts of Space Weather
  - "Electric power is modern society's cornerstone technology, the technology on which virtually all other infrastructures and services depend"
  - "Collateral effects of longer-term outage would likely include, for example, disruption of the transportation, communication, banking, and finance systems, and government services; the breakdown of the distribution of potable water owing to pump failure; and the loss of perishable foods and medications because of lack of refrigeration."
  - "…it is difficult to understand, much less predict, the consequences of future LF/HC events. Sustaining preparedness and planning for such events in future years is equally difficult."

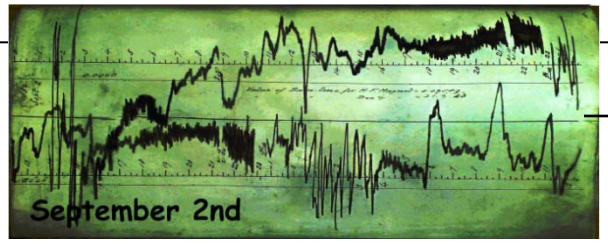
An Extreme Event: Carrington 1859



- Large geomagnetic storms can occur with smaller cycles

- The largest geomagnetic storms on record occurred during lower than average cycles



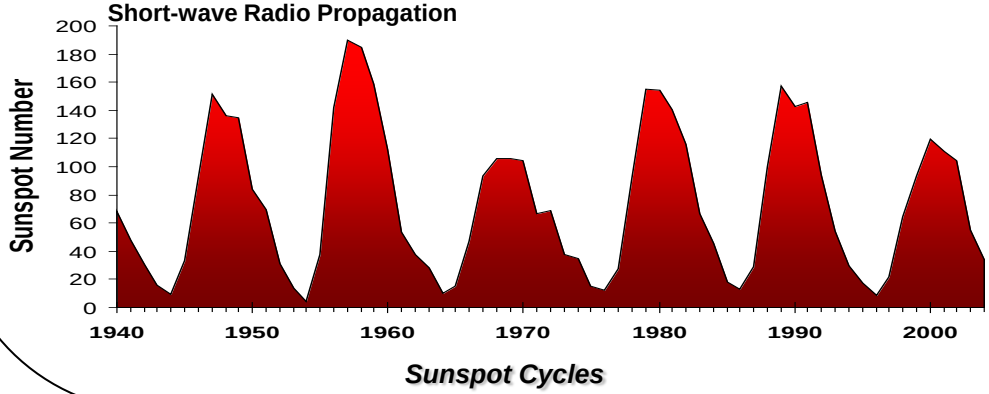


1859 Storm

1921 Storm

Growth of Space Weather Customers

Commercial Space Transportation
Airline Polar Flights
Microchip technology
Precision Guided Munitions
Cell phones
Atomic Clock
Satellite Operations
Carbon Dating experiments
GPS Navigation
Ozone Measurements
Aircraft Radiation Hazard
Commercial TV Relays
Communications Satellite Orientation
Spacecraft Charging
Satellite Reconnaissance & Remote Sensing Instrument Damage
Geophysical Exploration.
Pipeline Operations
Anti-Submarine Detection
Satellite Power Arrays
Power Distribution
Long-Range Telephone Systems
Radiation Hazards to Astronauts
Interplanetary Satellite experiments
VLF Navigation Systems (OMEGA, LORAN)
Over the Horizon Radar
Solar-Terres. Research & Applic. Satellites
Research & Operations Requirements
Satellite Orbit Prediction
Solar Balloon & Rocket experiments
Ionospheric Rocket experiments
Radar
Short-wave Radio Propagation



A few of the agencies and industries that rely on space weather services today:

- U.S. power grid infrastructure
- Commercial airline industry
- Dep. of Transportation (GPS)
- NASA human space flight activities
- Satellite launch and operations
- DoD Operations

DOE
Nuclear Reg Comm
Schlumberger
NY/PJM Grid

Ball
Loral
NESDIS/SOCC
Digital Globe

Boeing
Lockheed
Aerospace
Echostar

NASA
Space Command
ISS Astronauts
FAA

American
United Airlines
Northwest
Continental

New Drivers

2010-2020

An Evolving landscape: new technologies and capabilities will drive demand for space weather products

- Civil Precision GNSS Users
- Next Generation Air Transportation System
- Increased vulnerability of Power Grid
- Commercial Satellite Industry
- Exploration Mission to the Moon and beyond
- Commercial Space Enterprise
- Arctic Economic Development

New Drivers

Next Generation Air Transportation System (NextGen)

- NextGen to be GPS-based
- NWS responsible for primary areas of NextGen Weather Initiative
- Space weather requirements being defined

New Drivers

Increasing Power Grid Vulnerability

"The grid is becoming increasingly vulnerable to space weather events"

Future Directions in Satellite-derived Weather and Climate Information for the Electric Energy Industry – Workshop Report Jun 2004

$1-2 trillion | **Potential loss due to widespread power grid Blackout following severe geomagnetic storm**

4-10 years | **Recovery time from a widespread power grid Blackout following severe geomagnetic storm**

Source: National Academy Workshop on the Societal and Economic Impacts of Severe Space Weather Events held in Washington, D.C., May 2008.

Space Weather Now Part of U.N.

- World Meteorological Organization (WMO)
- International Civil Aviation Organization (ICAO)
- Committee on the Peaceful Uses of Outer Space (COPUOS)
- International Heliophysical Year (IHY)

International Space Environment Service (ISES)

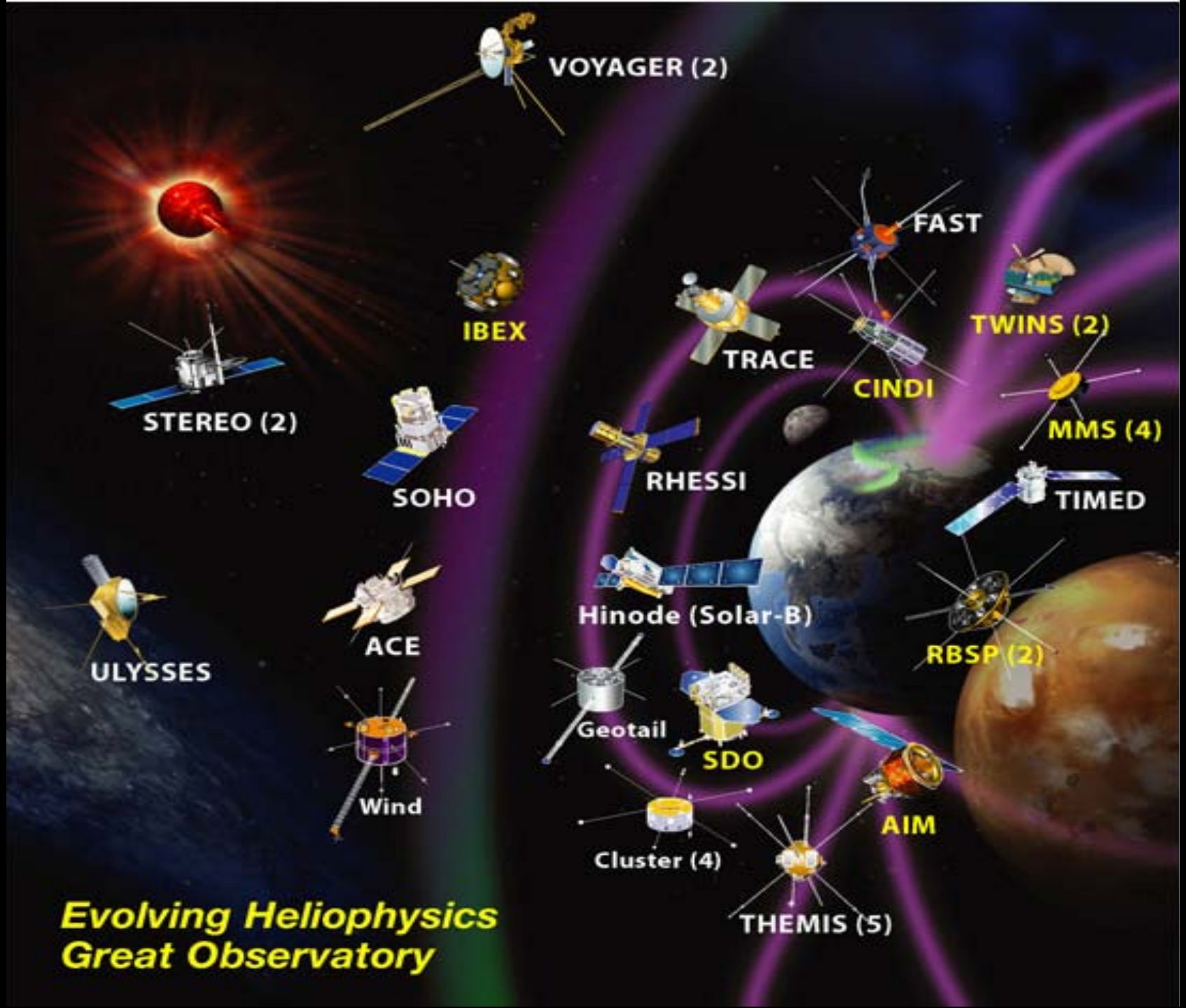
New Drivers

Space Weather Going Global

Benefits of International Collaboration

- Provides greater access to observations, research & modeling
- Improves skill of forecasts
- Improves regional expertise
- Specialization in space weather science & services

All will reduce space weather threats to society

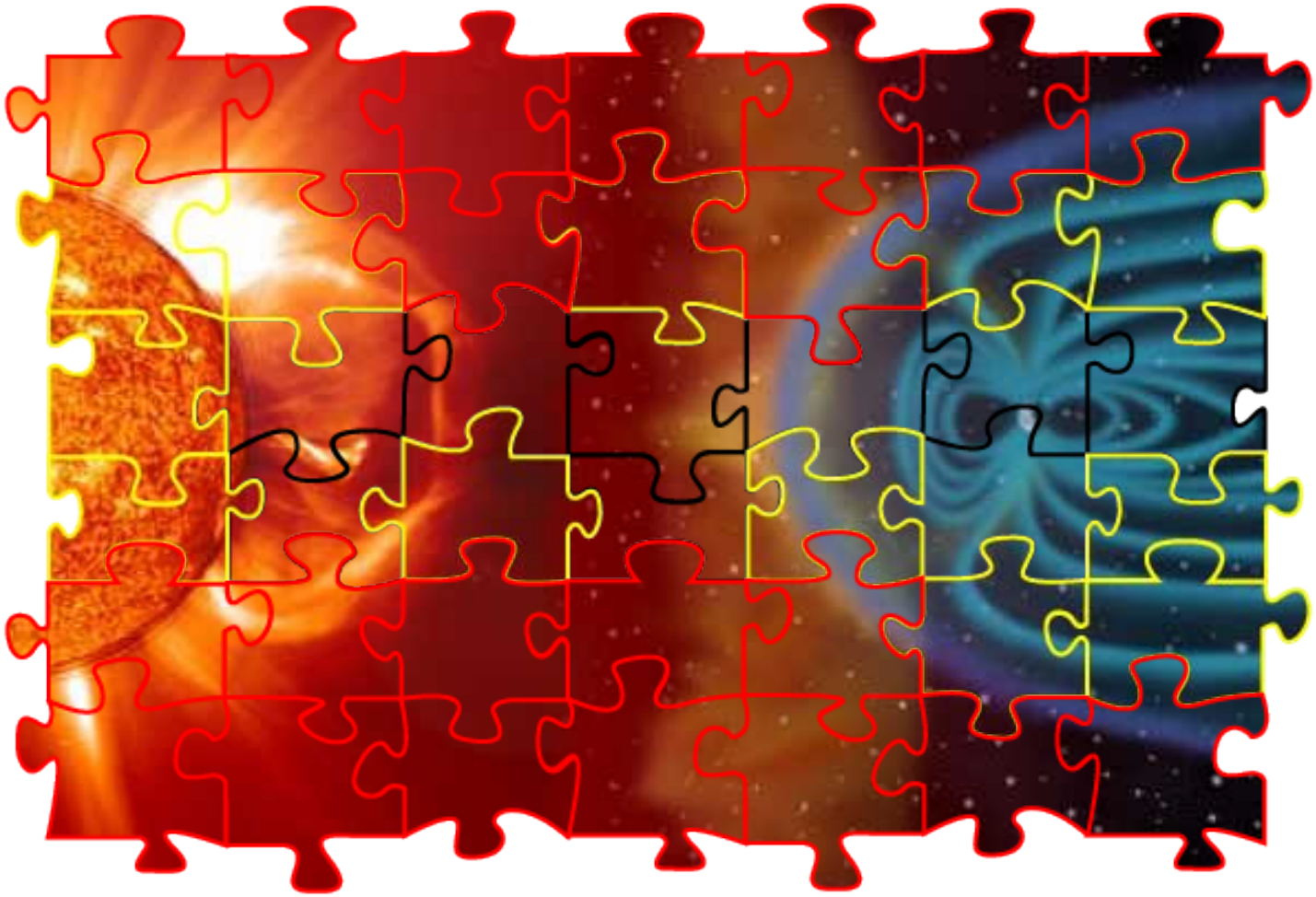

VOYAGER (2)
FAST
IBEX
TWINS (2)
TRACE
CINDI
STEREO (2)
MMS (4)
RHESSI
SOHO
TIMED
Hinode (Solar-B)
ACE
ULYSSES
RBSP (2)
Geotail
SDO
Wind
AIM
Cluster (4)
THEMIS (5)
Evolving Heliophysics
Great Observatory

International Living With a Star (ILWS)

Courtesy of Prof. I. Mann

Solving The Space Weather Puzzle

Heliophysics Summer School - 2010



CISM Core

CISM Partners

Community

Summary

- The challenges of space weather affect all developed countries and both civilian and military systems
- Work on space weather specification, modeling, and forecasting has great societal benefit: It is basic research with a high public purpose
- Future space exploration and most modern human endeavors will require major advances in physical understanding and improved transition of space research to operations

Thank you.

Questions?