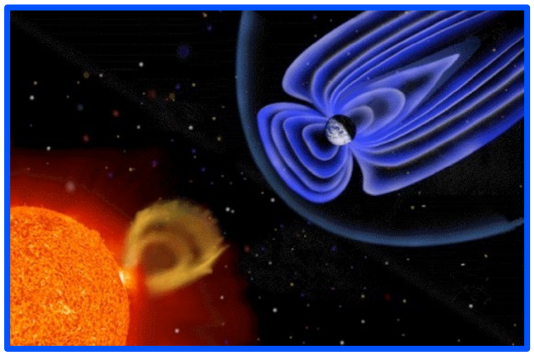
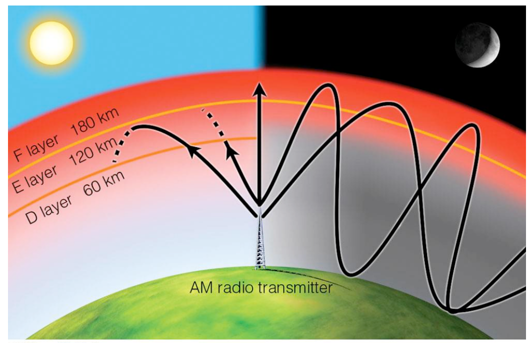
Space Weather Near An Average Sized Star: From Physics to Technology Impacts in the Coupled Geospace System



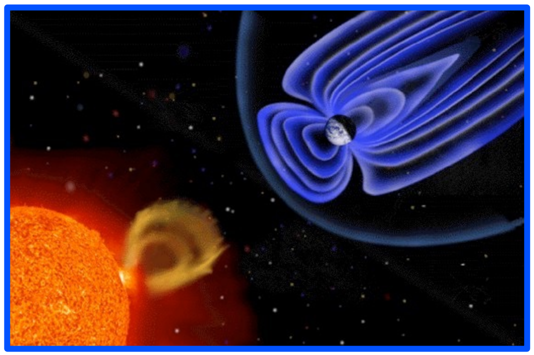


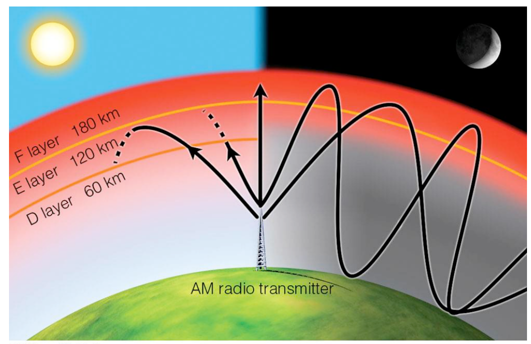
Dr. Philip Erickson
Atmospheric and Geospace Sciences Group
MIT Haystack Observatory
Westford, MA 01886 USA

Thanks: D. N. Baker, L. Lanzerotti, J. Thayer, A. Viljanen,
MIT Haystack AGS Group, NSF, NASA

IEEE PES Boston July 20, 2016

Space Weather Near An Average Sized Star: From Physics to Technology Impacts in the Coupled Geospace System





Outline:

- Space weather history
- The geospace system
- Space weather technology impacts
- Some general comments

Italy Blames Disruption of Comsat NATO Uses on Strong Solar Activity

PETER B. de SELDING, PARIS

The Italian Defense Ministry lost control of its ... cause we really didn't know what was going on." In response to Space News questions, the Italian joint de- ... software modernization ... satellite, which is at the h... point in its scheduled o... ing life."

Space News, January 15, 2007

For Manned Deep-Space Missions, Radiation Is Biggest Hurdle

by Mike Wall, SPACE.com Senior Writer
Date: 20 December 2012 Time: 07:00 AM ET

...e Hamilton Sp...

P-ANIK!

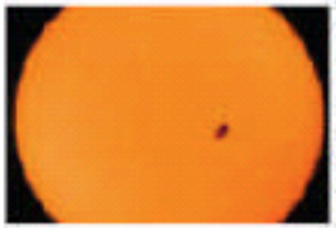
High-tech chaos as satellites spin out of control

Plug pulled on phones, TV, radio, papers

YAHOO! NEWS

Space weather could wreak havoc in gadget-driven world

by Kerry Sheridan



Space Station Glitch Possibly Caused by Solar Flare

By Tariq Malik
Staff Writer
posted: 15 December 2006
11:49 am ET

Updated at 2:40 p.m. EST

MONDAY, JULY 17, 2000

Solar storm ends up just a nuisance

REUTERS

WASHINGTON — A severe geo...

THE CLEVELAND LEADER

LOCAL | US & WORLD | ENTERTAINMENT | BUSINESS/TECH | SPORTS | HEALTH/SCIENCE | LIFESTYL...

SPACE TRAVEL COULD BE DEALT A BLOW WITH DISCOVERY THAT COSMIC RADIATION COULD CAUSE ALZHEIMER'S DISEASE

January 1, 2013 - 11:59am by Julie Kent

Solar Storms Cut Airplane Radio Contact

By Tom Cohen
Associated Press
posted: 04:00 am ET
30 October 2003

A4 Daily Record, Morris County, N.J., Thursday, September 8, 2005

Solar flare may disrupt communications

WASHINGTON (AP) — A ...lar flare was reporte... ...day and forecasters ... of potential electrica... ...munications disrup... ...are was reported by

THE NEW YORK TIMES, WEDNESDAY, MARCH 8, 1989

Largest Solar Flaring in 5 Years Could Break Up Communications

By WILLIAM K. STEVENS

PLANET EARTH

Magnetic North Pole Shifts, Forces Runway Closures at Florida Airport

By Jeremy A. Kaplan
Published January 06, 2011 | FoxNews.com

YAHOO! NEWS March 10, 2011

Major Solar Flare Erupts, May Make Auroras Visible in Northern U.S.

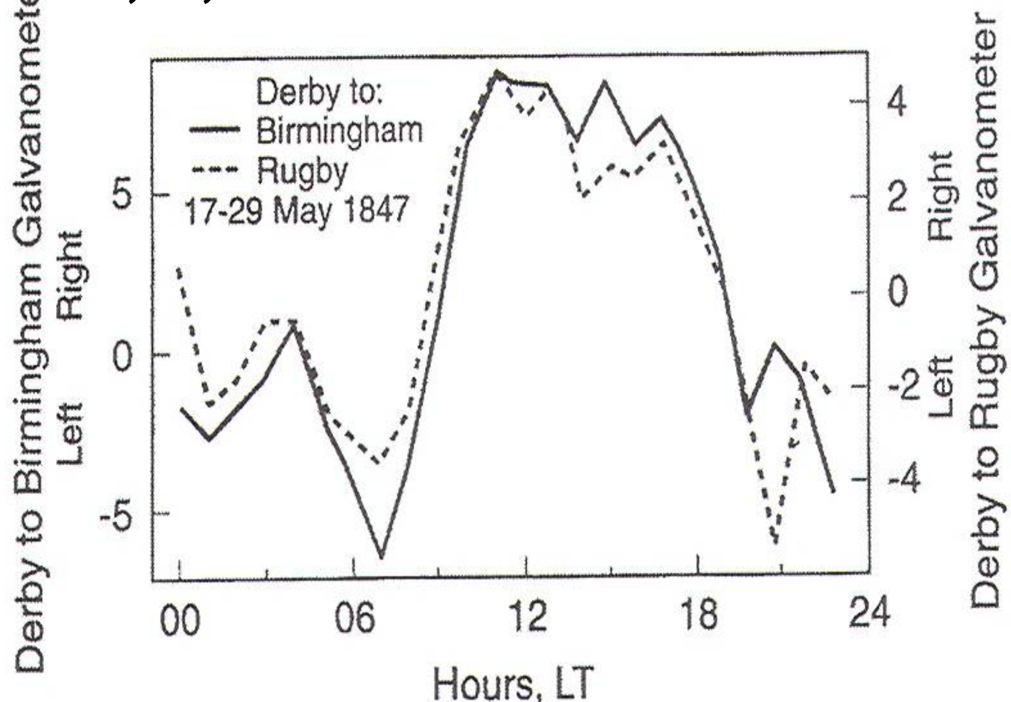
Space.com
Thu Mar 10, 4:45 pm ET

(courtesy L. Lanzerotti, NJIT)

Telegraphs in the 1840s

W. H. Barlow, "On spontaneous electrical currents observed in the wires of the electric telegraph", *Phil. Trans. R. Soc.*, 61, 1849

"THE OBSERVATIONS DESCRIBED ... WERE UNDERTAKEN IN CONSEQUENCE OF CERTAIN *SPONTANEOUS DEFLECTIONS* HAVING BEEN NOTICED IN THE NEEDLES OF THE ELECTRIC TELEGRAPH ON THE MIDLAND RAILWAY, THE ERECTION OF WHICH WAS CARRIED OUT UNDER MY SUPERINTENDENCE AS THE COMPANY'S ENGINEER."



"... in every case which has come under my observation, the telegraph needles have been deflected whenever aurora has been visible"

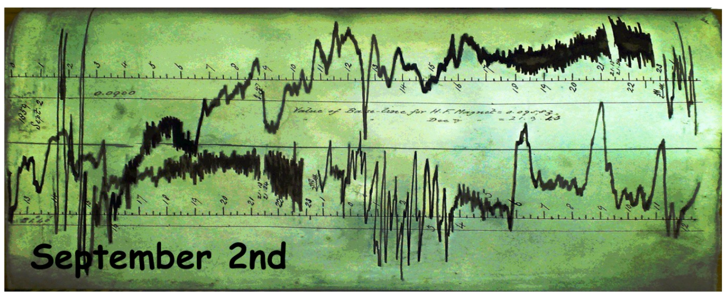
Space weather
Ionosphere daily variations inducing daily ground current variations

(courtesy L. Lanzerotti, NJIT)

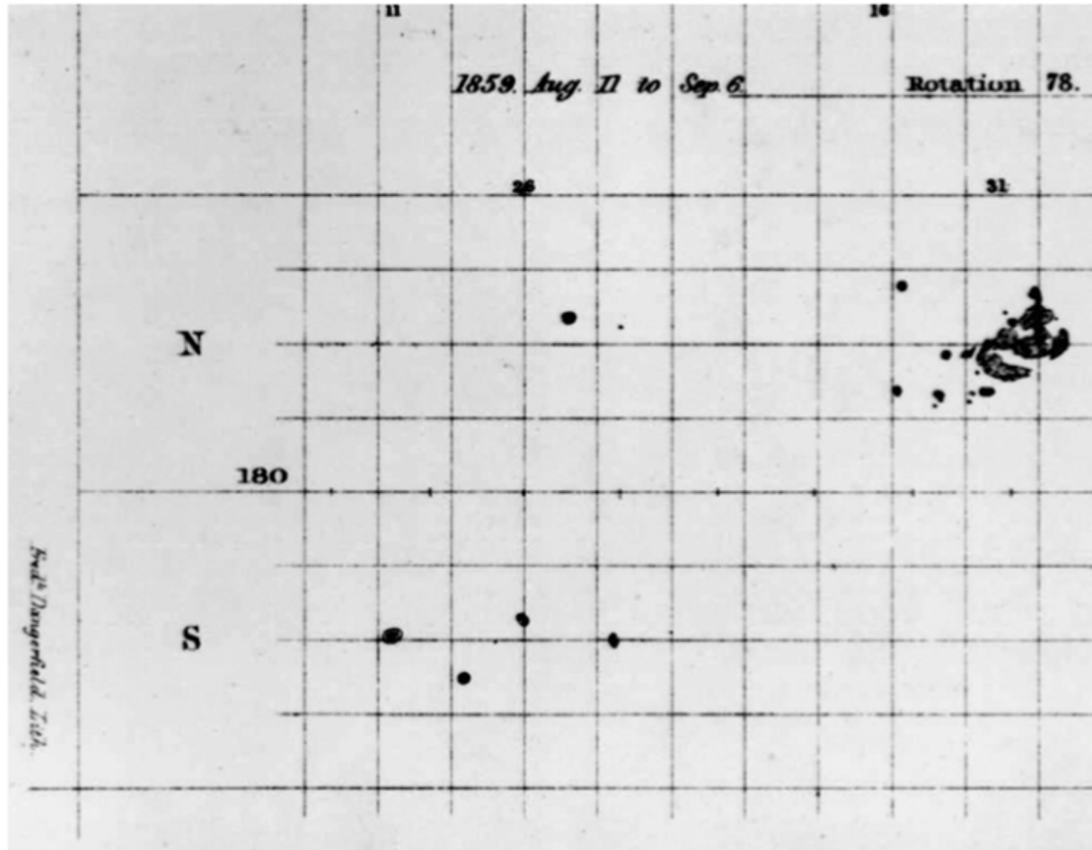
The 'Carrington Event': Aug 27 – Sep 7, 1859

"two patches of intensely bright and white light broke out, in the positions indicated in fig. 1 ... My first impression was that by some chance a ray of light had penetrated a hole in the screen attached to the object glass, for the brilliancy was fully equal to that of direct sun-light"

R. C. Carrington



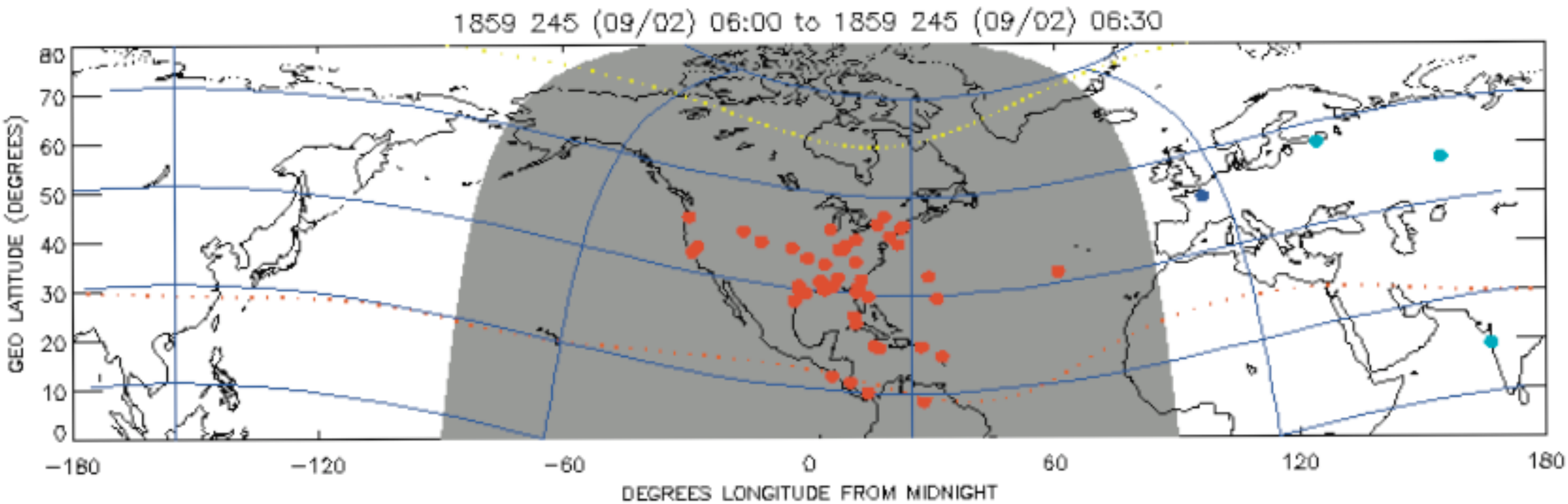
Magnetometer traces
Greenwich Royal Observatory
Greenwich, England



Carrington sunspot drawings (Carrington, 1863)
Rare white light intensification seen

Still the largest geomagnetic disturbance on record at Earth
(and largest for ~500 years)

The 'Carrington Event': Aug 27 – Sep 7, 1859



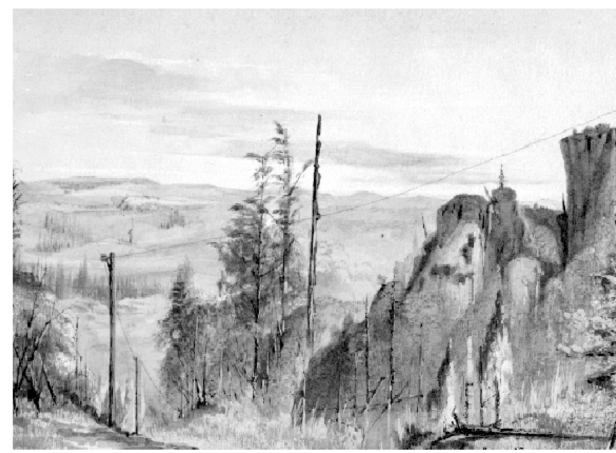
Locations where aurora was visible
(Green, 2008)

The ‘Carrington Event’: Aug 27 – Sep 7, 1859

Boston MA to Portland ME telegraph line
Sept 2, 1859

“We observed the influence upon the lines at the time of commencing business — 8 o’clock — and it continued so strong up to 9 1/2 as to prevent any business from being done, excepting *by throwing off the batteries at each end of the line and working by the atmospheric current entirely!*”

NY Times



Operator exchange:

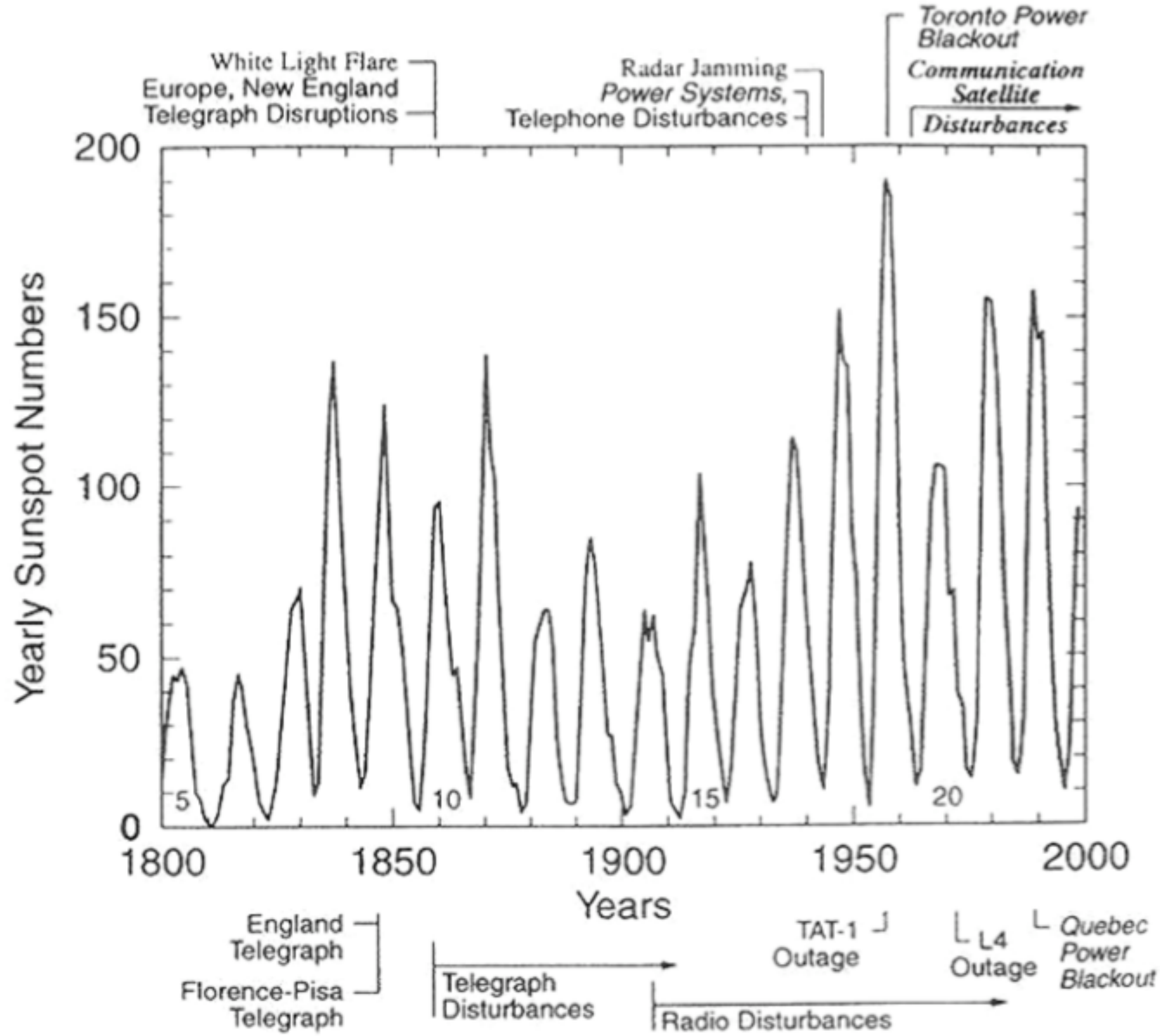
BOS: Mine is also disconnected, and we are working with the auroral current. How do you receive my writing?

POR: Better than with our batteries on..

Very well. Shall I go ahead with business?

Telegraph and Radio Disturbances in the 19th. 20th Centuries

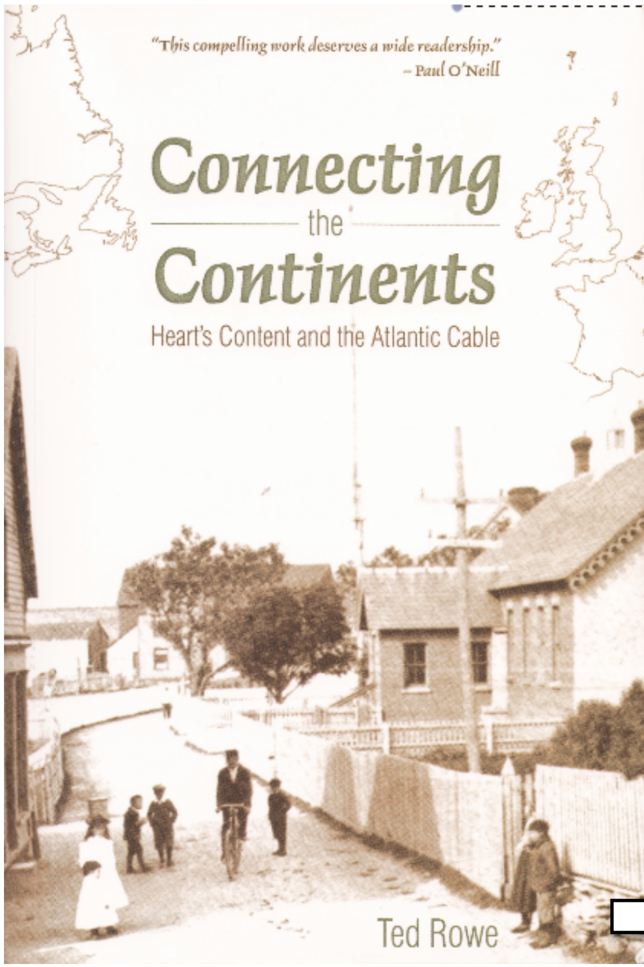
- Breit and Tuve (1925), Appleton and Barnett (1925) identify ionospheric radio reflection layer
- Correlation between HF propagation and solar activity first identified in 1932 (Marconi hinted at this earlier)
- Serious impacts to transatlantic communications: Wavelength diversity used to combat transmission corruptions
- Sunspot number used as a early form of space weather prediction by HF operators - continues today as a tool by the amateur radio community

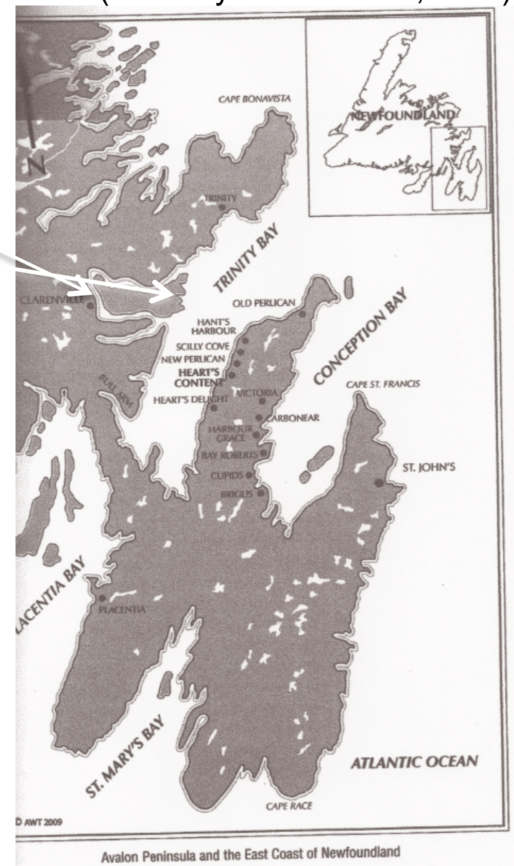


(Lanzerotti, 2001)

Atlantic Telegraph Cables

(courtesy L. Lanzerotti, NJIT)





Old telegraph cables from Trinity Bay into telegraph station
Today: A Newfoundland Provincial Historical site

Space weather on the first Atlantic telegraph cable

"… the beginning of cable service was far from reliable….earth's magnetic currents, lightning, the aurora borealis … sent the [galvanometer] into wild and rapid gyrations." T. Rowe, ***Connecting the Continents***, 2009.

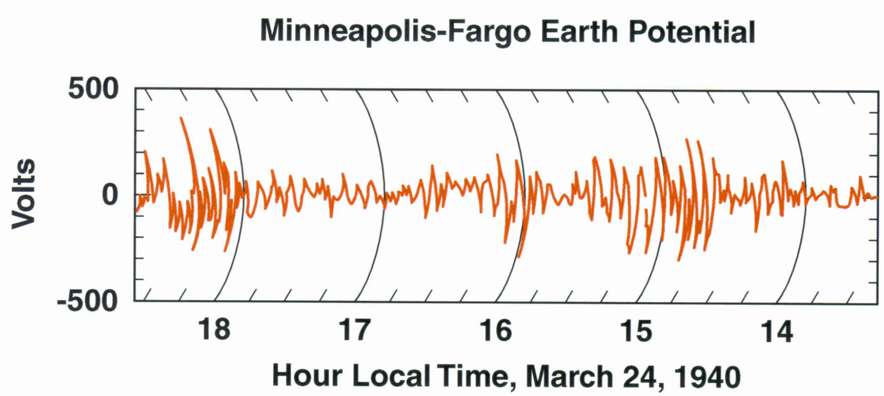
IEEE PES Power & Energy Society®

IEEE

Magnetic Storm: March 24, 1940

Numerous Problems (Transformer Tripping; Reactive Power Surges) on Systems
e.g.: Philadelphia Electric; Public Service NJ; Central Maine;
Northern States Power (MN); Eastern MA Electric
Transformer Tripping, Ontario Hydro Electric Commission
4 Transformer Banks, Chats Falls, Niagara District (220kV)
6 Transformer Banks, Abatibi System (132 kV)

Widespread effects on Radio- and Landline-telephony



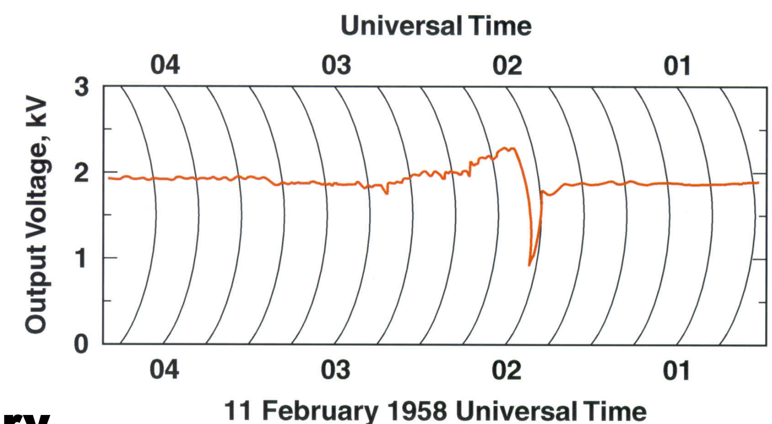
Leads to:
Major industrial conference
Power and telecom companies

Magnetic Storm: February 10, 1958

"At almost the exact moment when the magnetograph traces leaped and the aurora flared up, huge currents in the earth, induced by the heavenly turbulence, manifested themselves not only in power lines in Canada but in *cables under the north Atlantic*."*

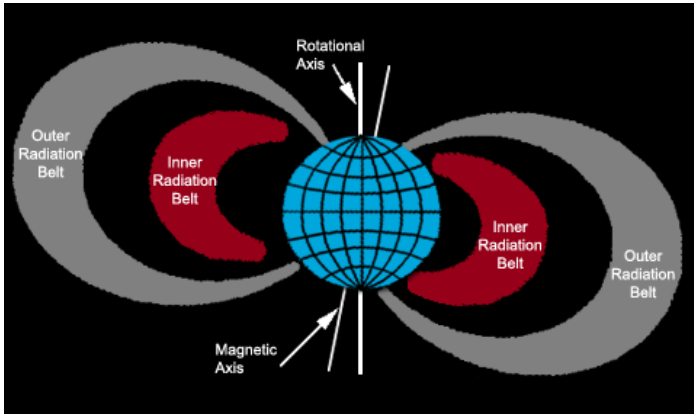
"… Circuit breakers began tripping out in Ontario transformer stations, plunging the Toronto area into a temporary darkness broken only by the strange light of the aurora overhead"*

Voltage on first transatlantic telephone cable
Oban, Scotland



*John Brooks, "A Reporter at Large; The Subtle Storm," *New Yorker*, February 19, 1959

Man-Made Space Weather

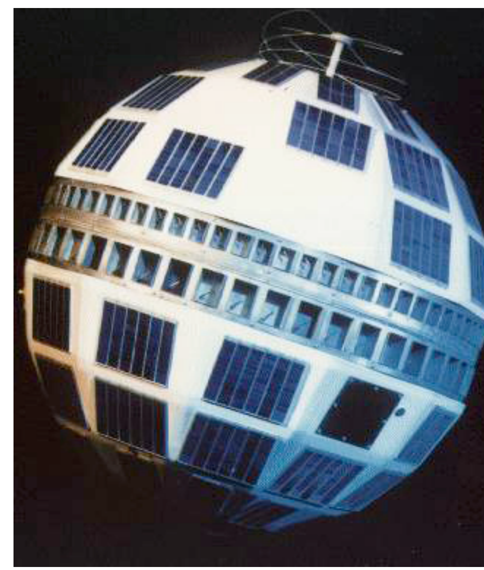


Van Allen inner, outer radiation belts

Start at ~400 km altitude
First discovered 1958
(Explorer 1, 3)

Starfish Prime
9 July 1962

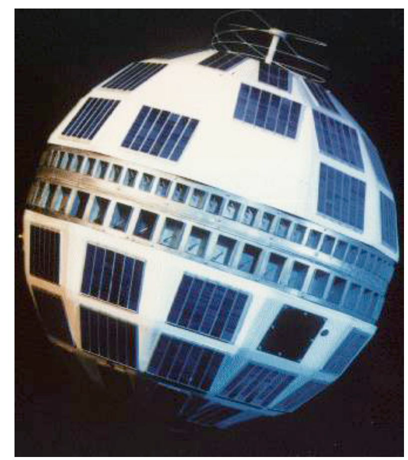
Telstar 1
Bell Systems
launched 10 July 1962
failure early 1963



Space Weather and Technology

<u>As the complexities of technical systems increase</u>, as new technologies are invented and employed, human-built systems themselves become more susceptible to the effects of Earth's space environment.

-- Lanzerotti



Sun-Earth System Overview

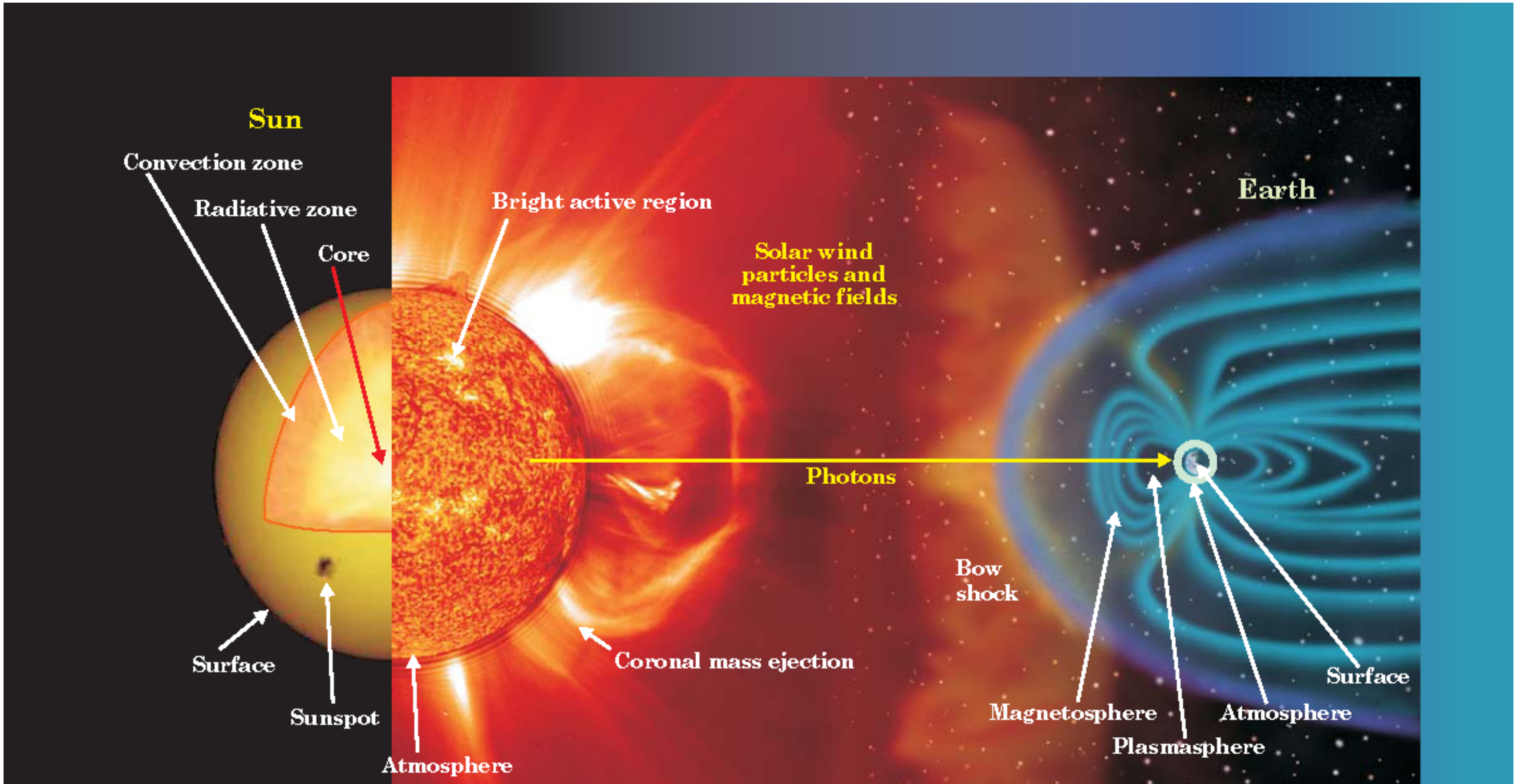
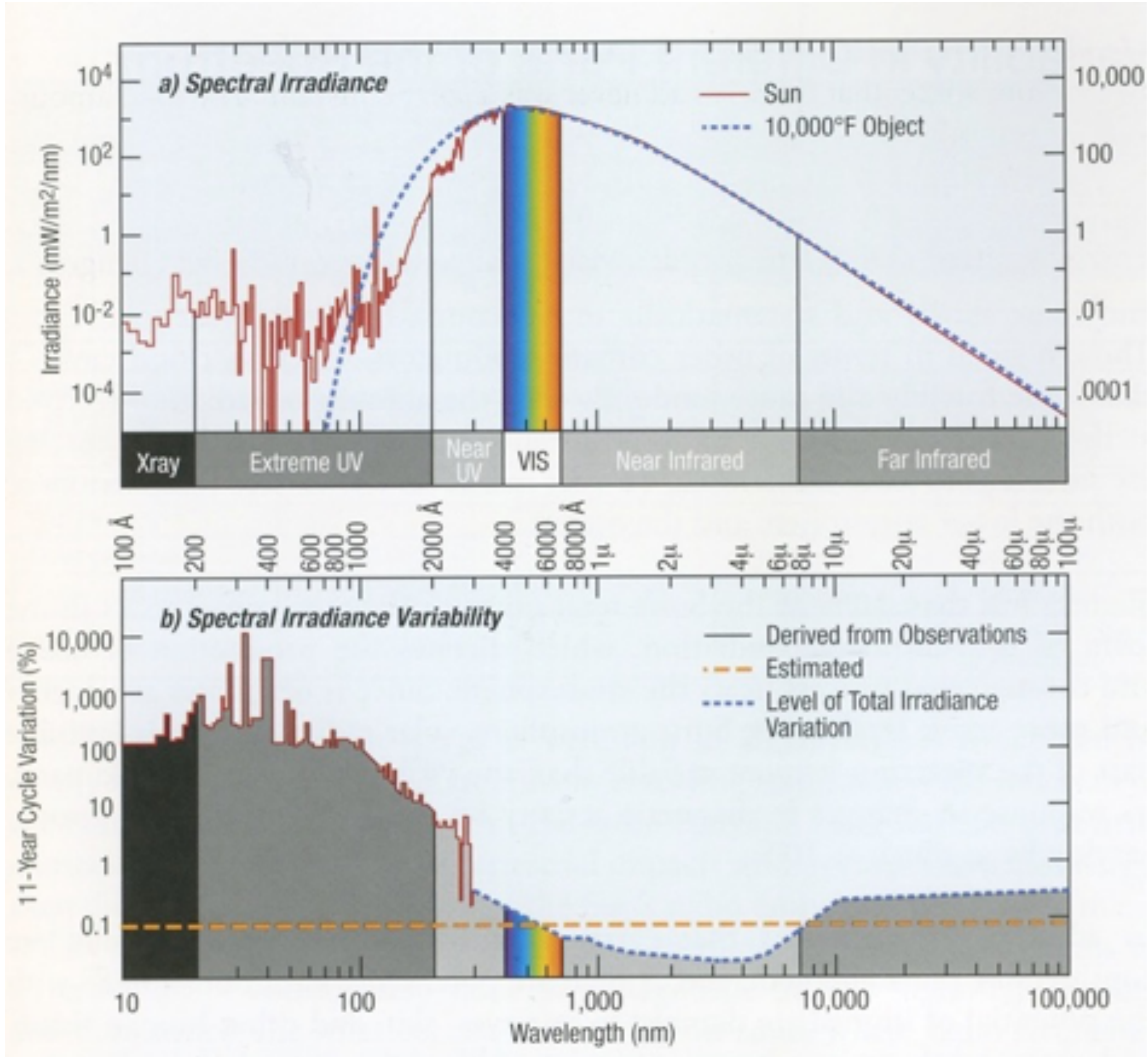
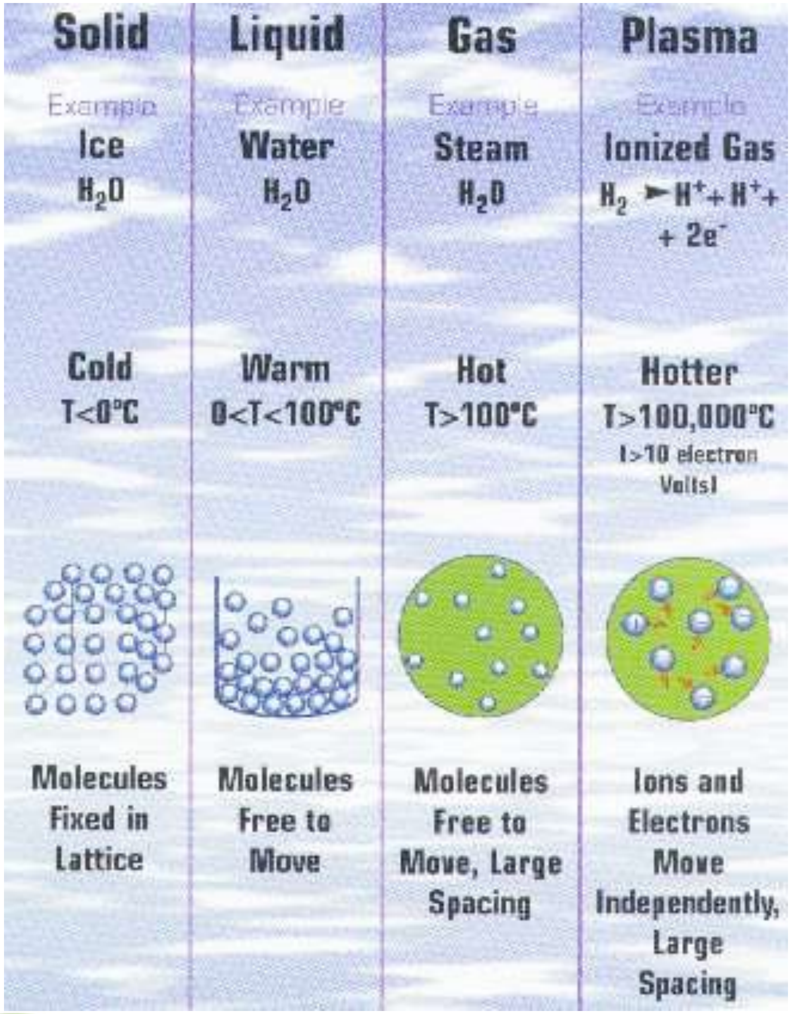


Figure 1. The Sun–Earth system. Energy in various forms is constantly flowing from the Sun to Earth. Dynamo action in the convection zone drives variations in this energy flow by producing sunspots and bright active regions. Photons from the Sun's surface and atmosphere reach Earth's surface and atmosphere, but particles and fields that together form the solar wind are intercepted by the magnetosphere (blue). Eruptive events such as coronal mass ejections, shown emerging from the Sun's atmosphere into the solar wind, perturb the magnetosphere and allow energetic particles to penetrate Earth's atmosphere in the polar regions, where the magnetic field lines are anchored. (Figure not to scale.)

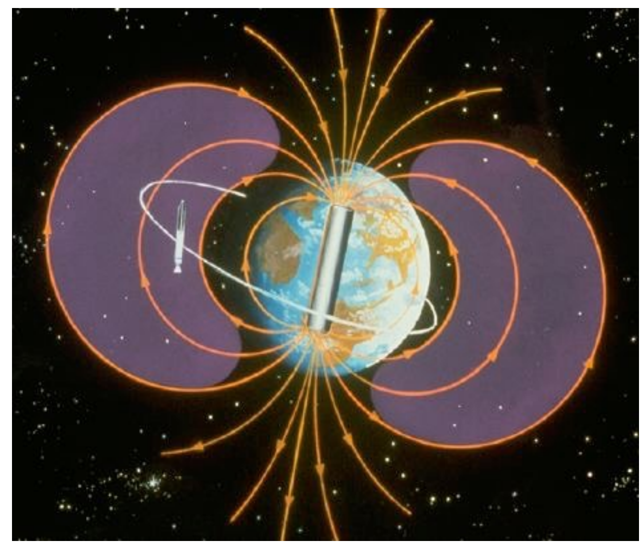
Solar Output Variability As a Function Of Wavelength



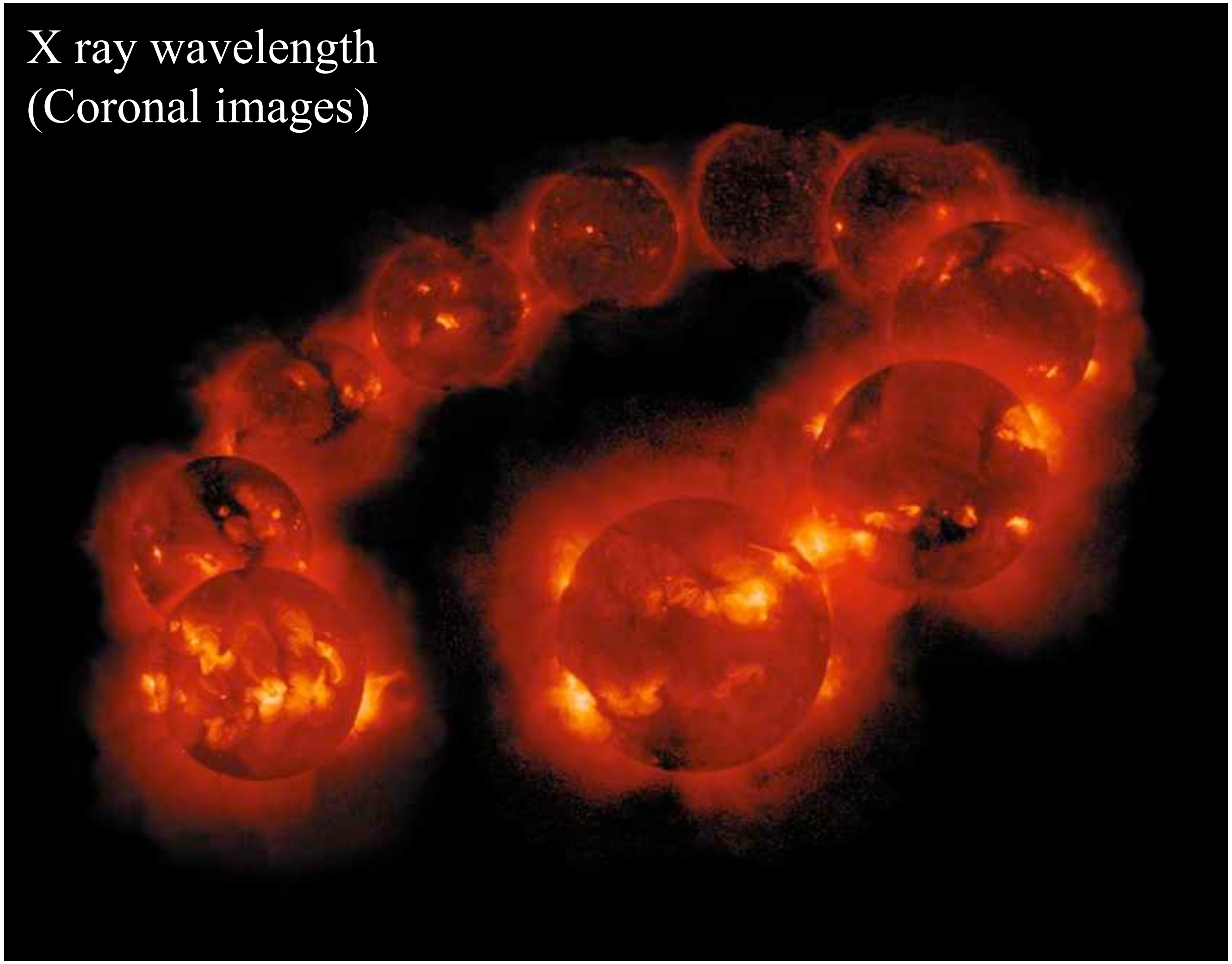
A Natural Plasma: Earth's Upper Atmosphere



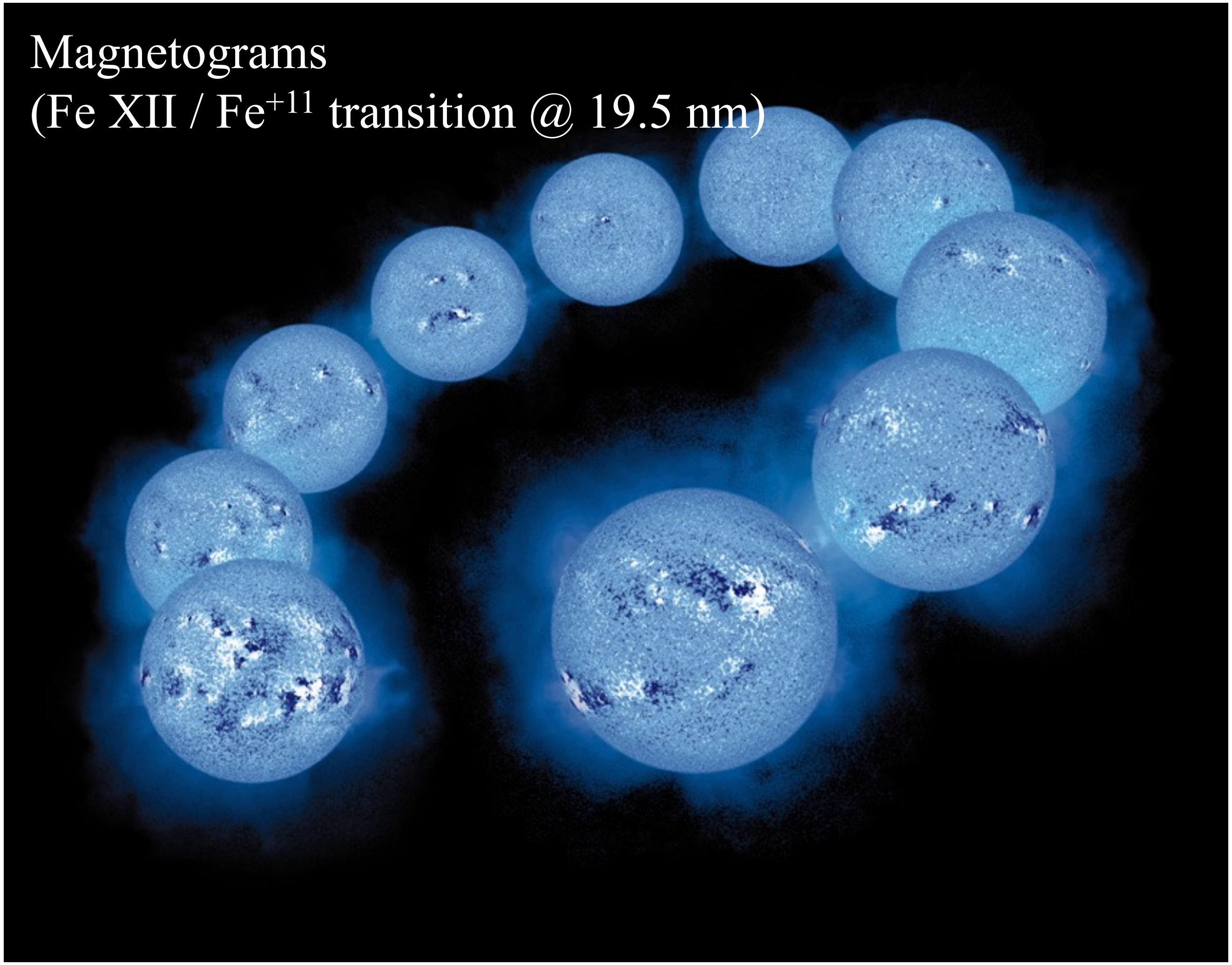
- Plasma is the fourth state of matter
- The universe is filled with plasma
- Extreme ultraviolet output from the Sun creates a plasma in Earth's heavily magnetized upper atmosphere through ionization



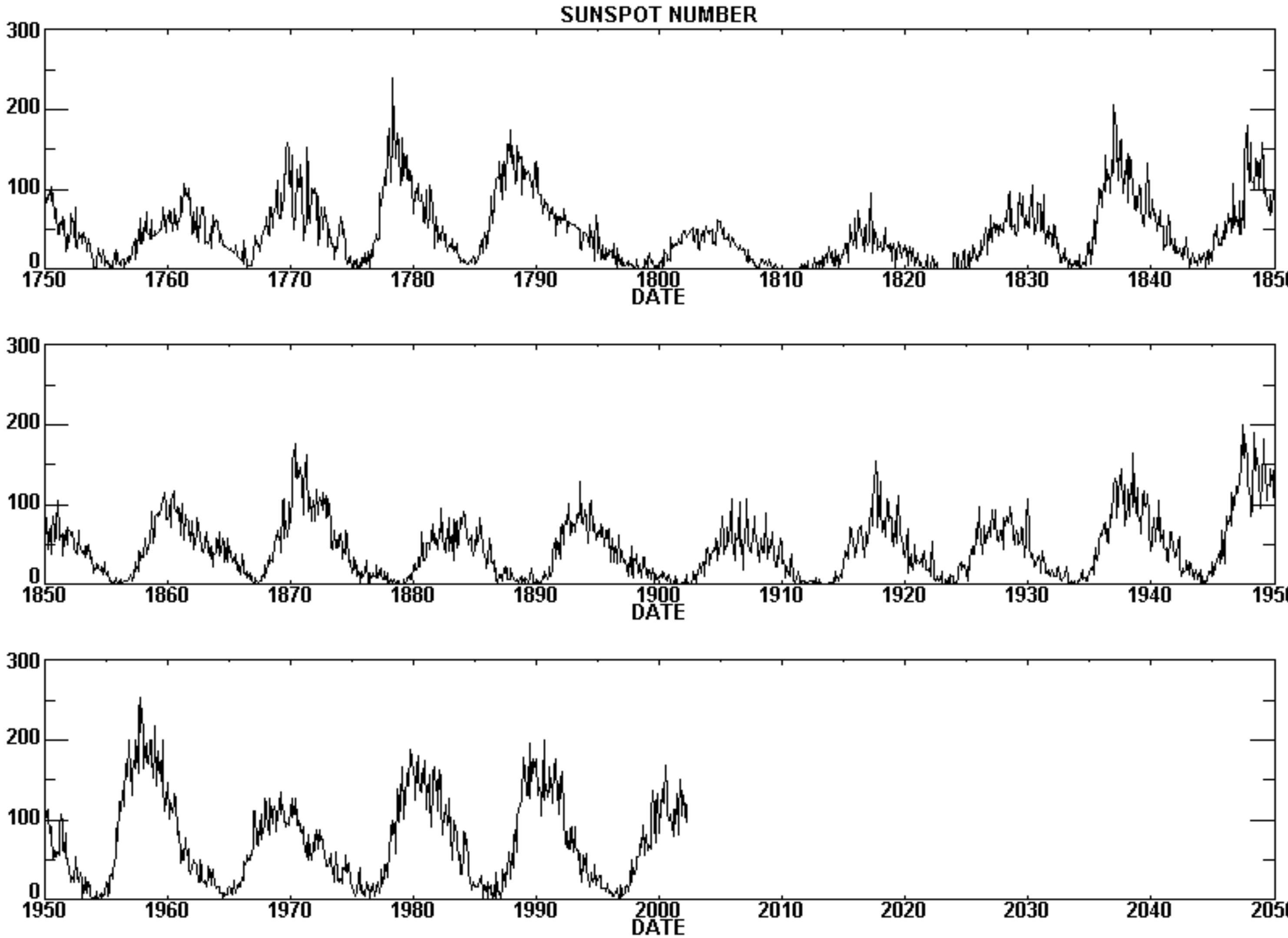
The Solar Cycle: Solar Variability



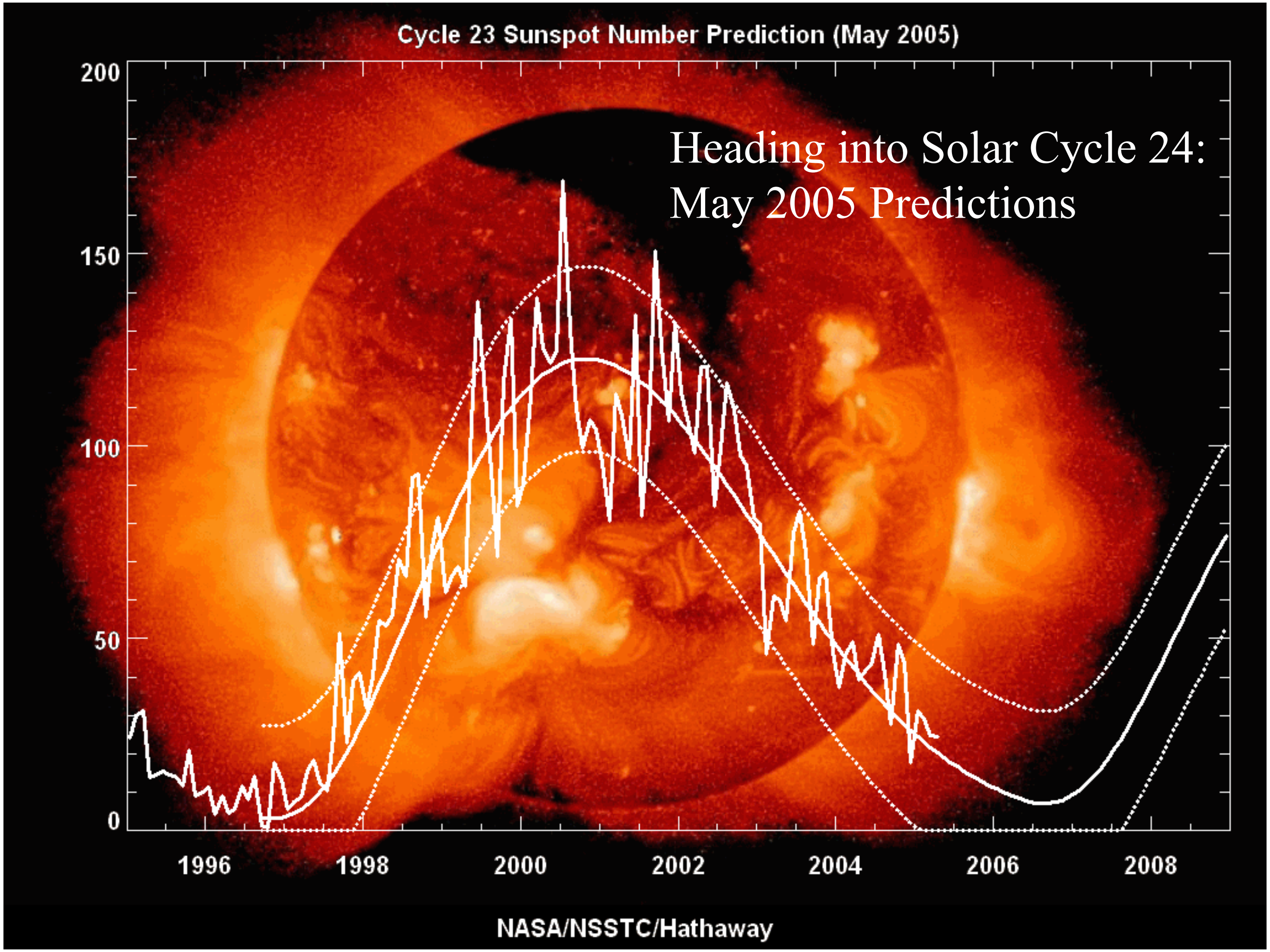
The Solar Cycle: Solar Variability



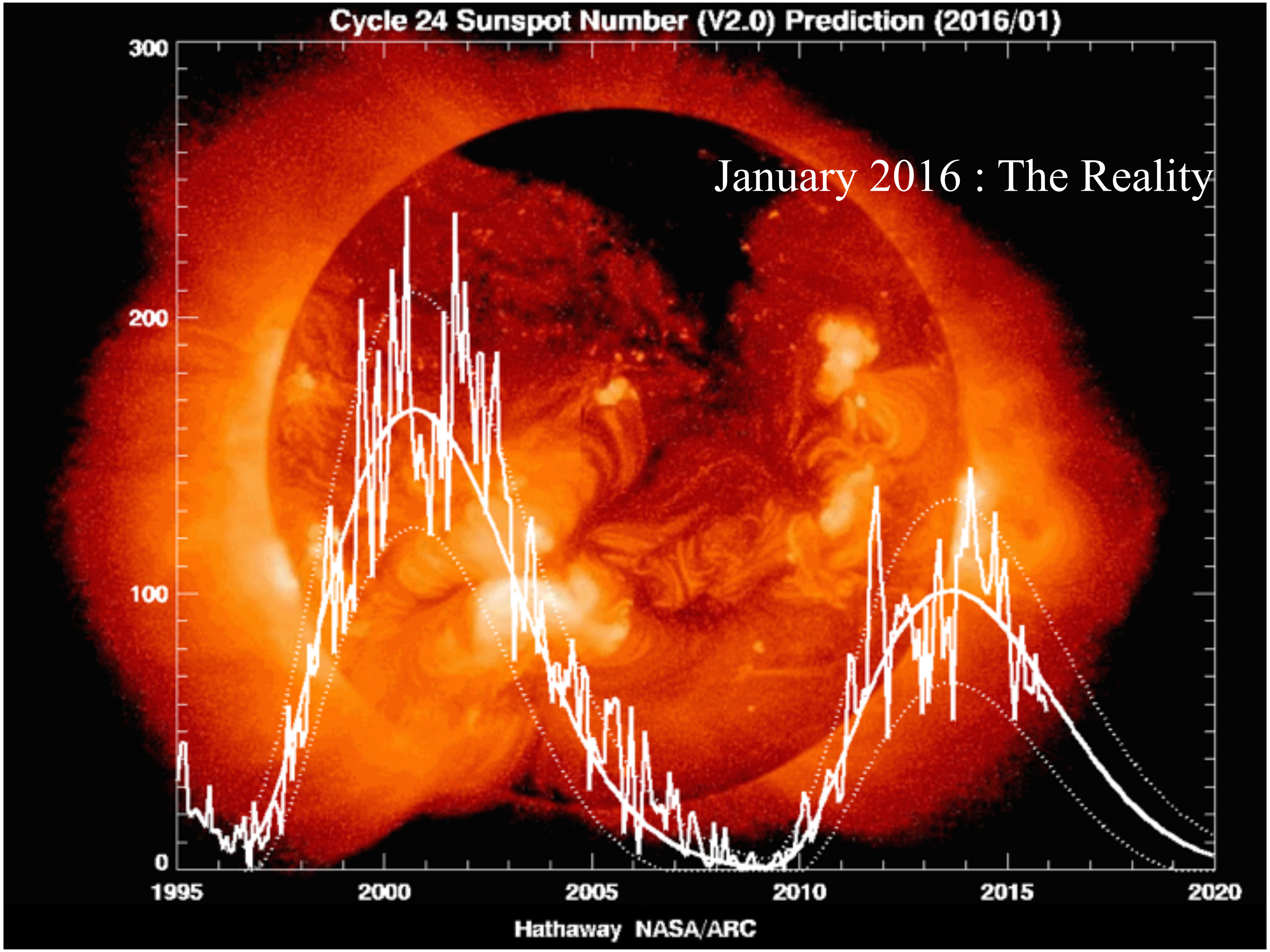
The Solar Cycle: Long-Term Variations



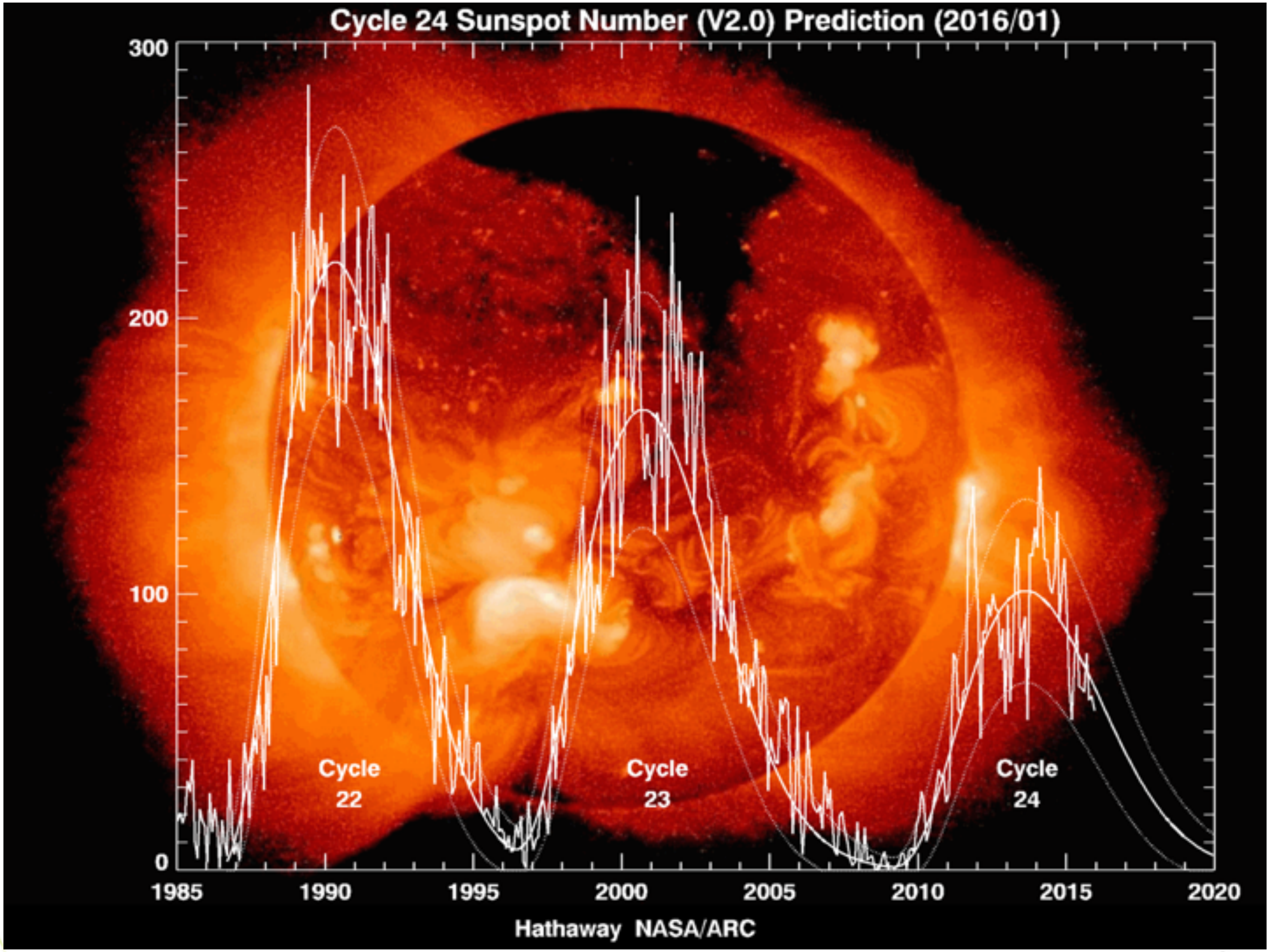
Predicting Solar Variability



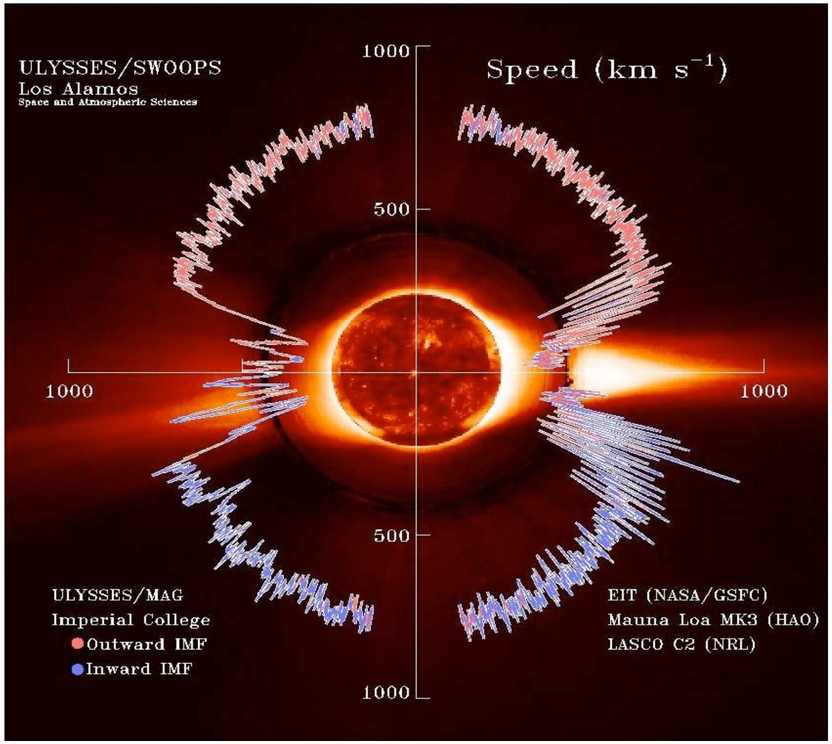
Predicting Solar Variability



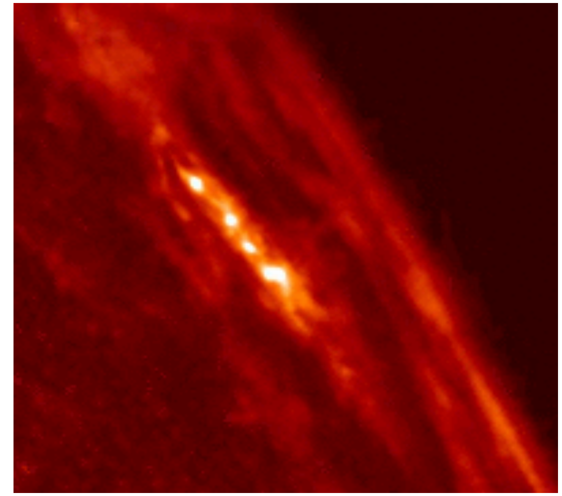
Solar Cycle: The Recent Past



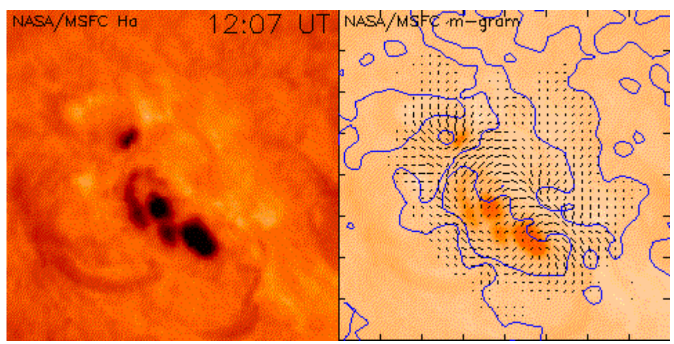
Solar Phenomena



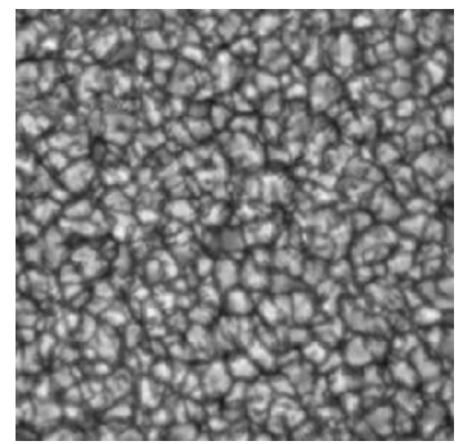
Solar Wind



Flares

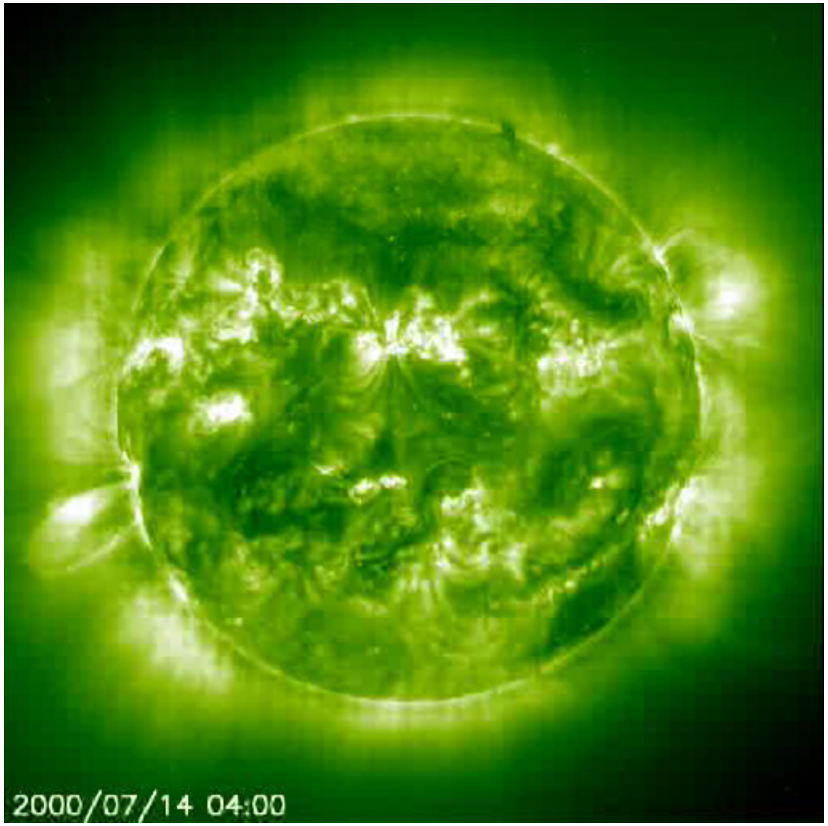


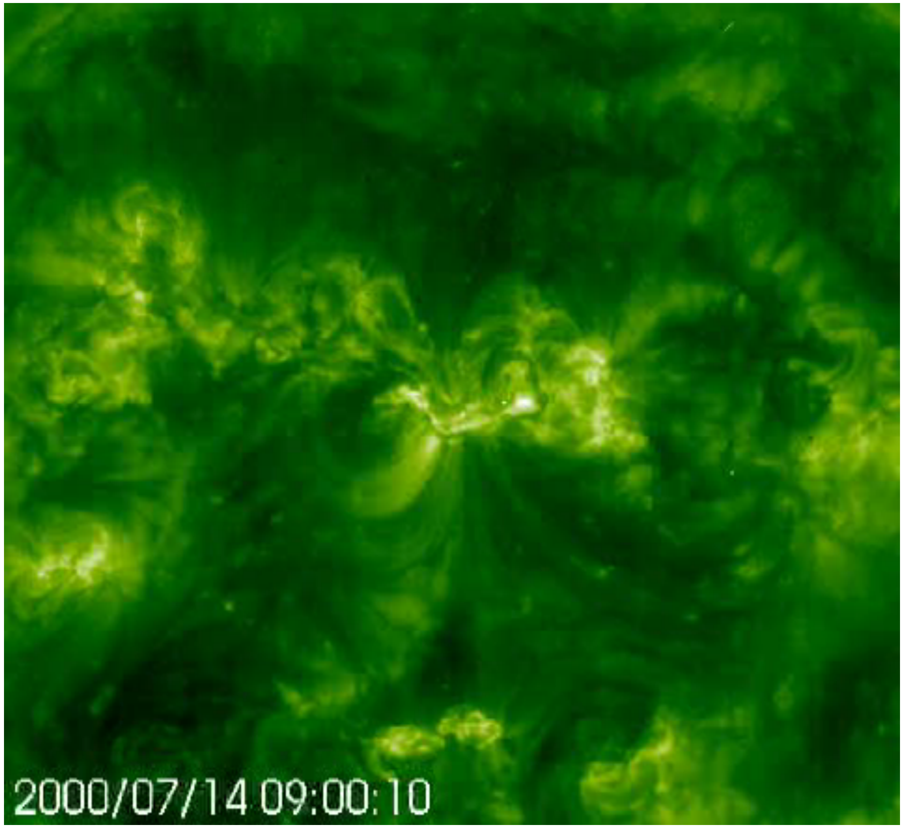
Sunspots



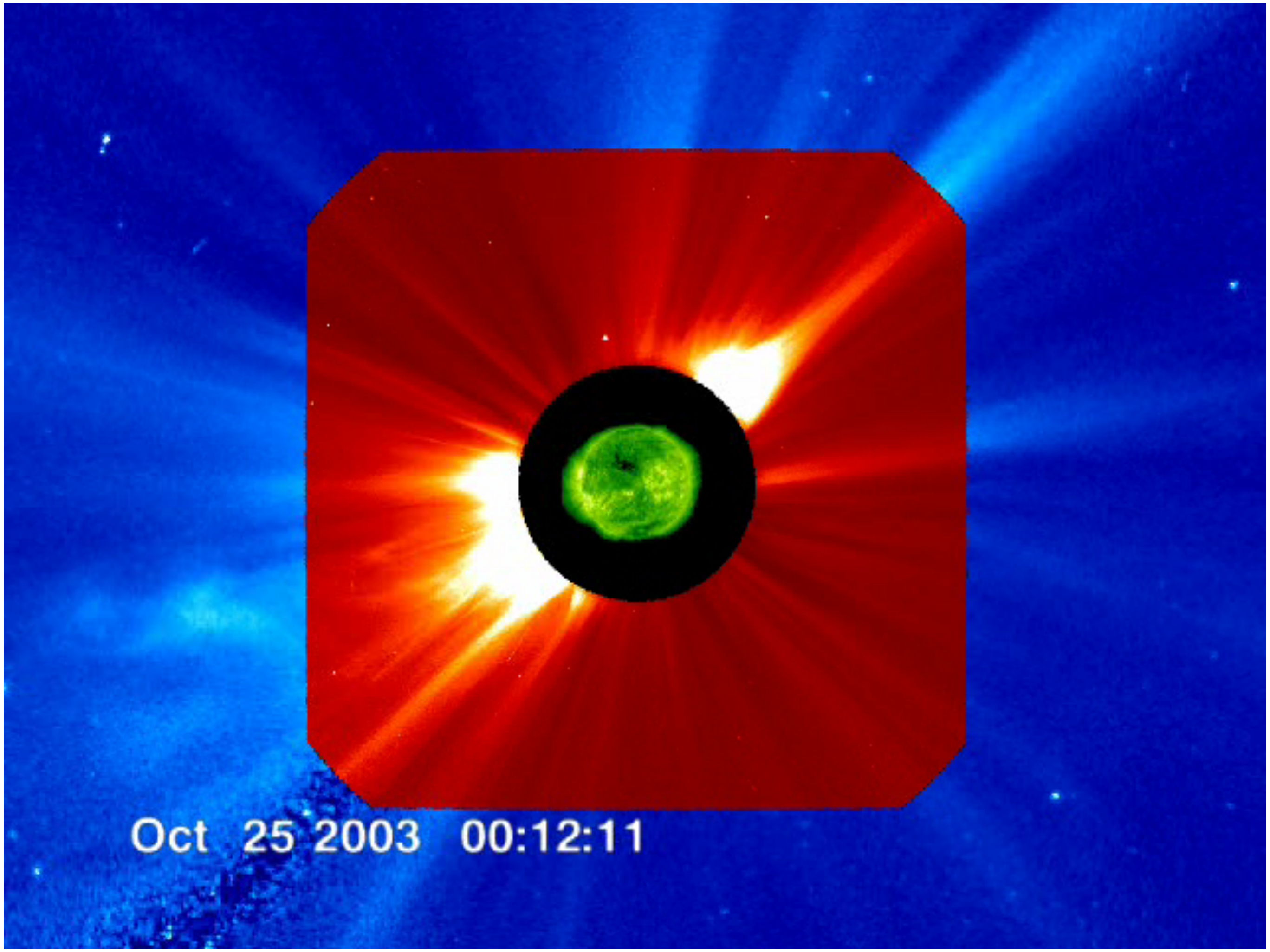
Granulations

Coronal Mass Ejections

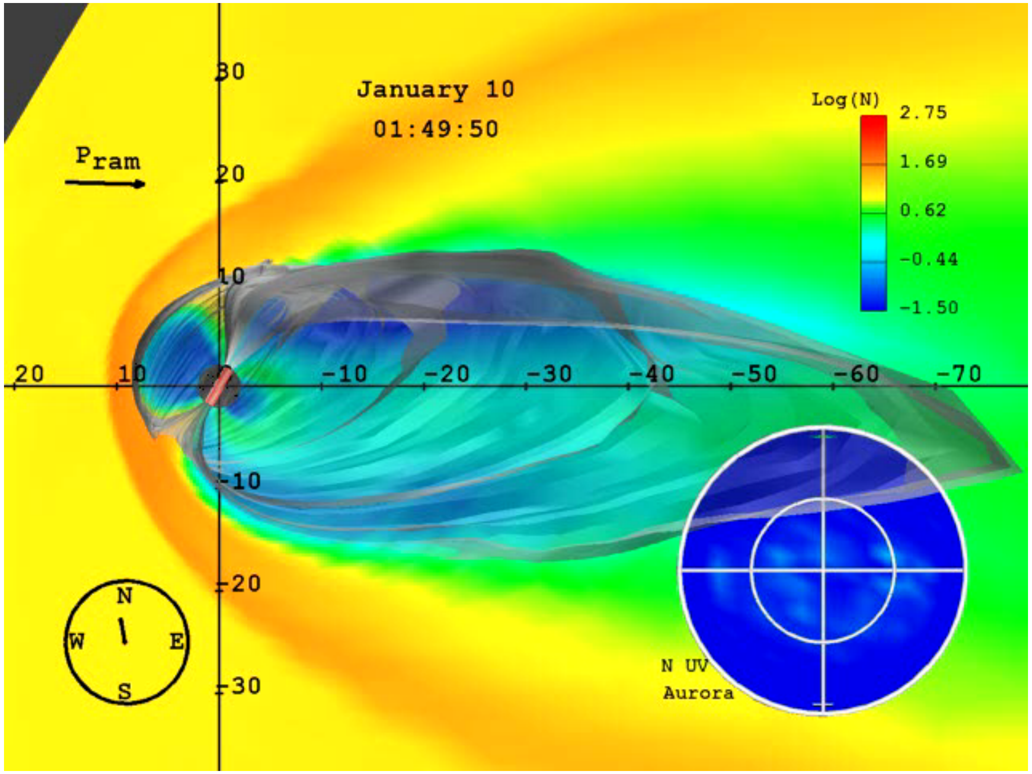


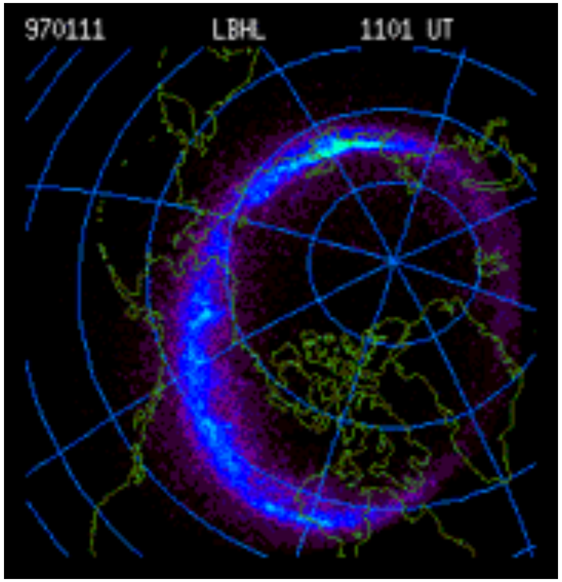


The Halloween 2003 Storm



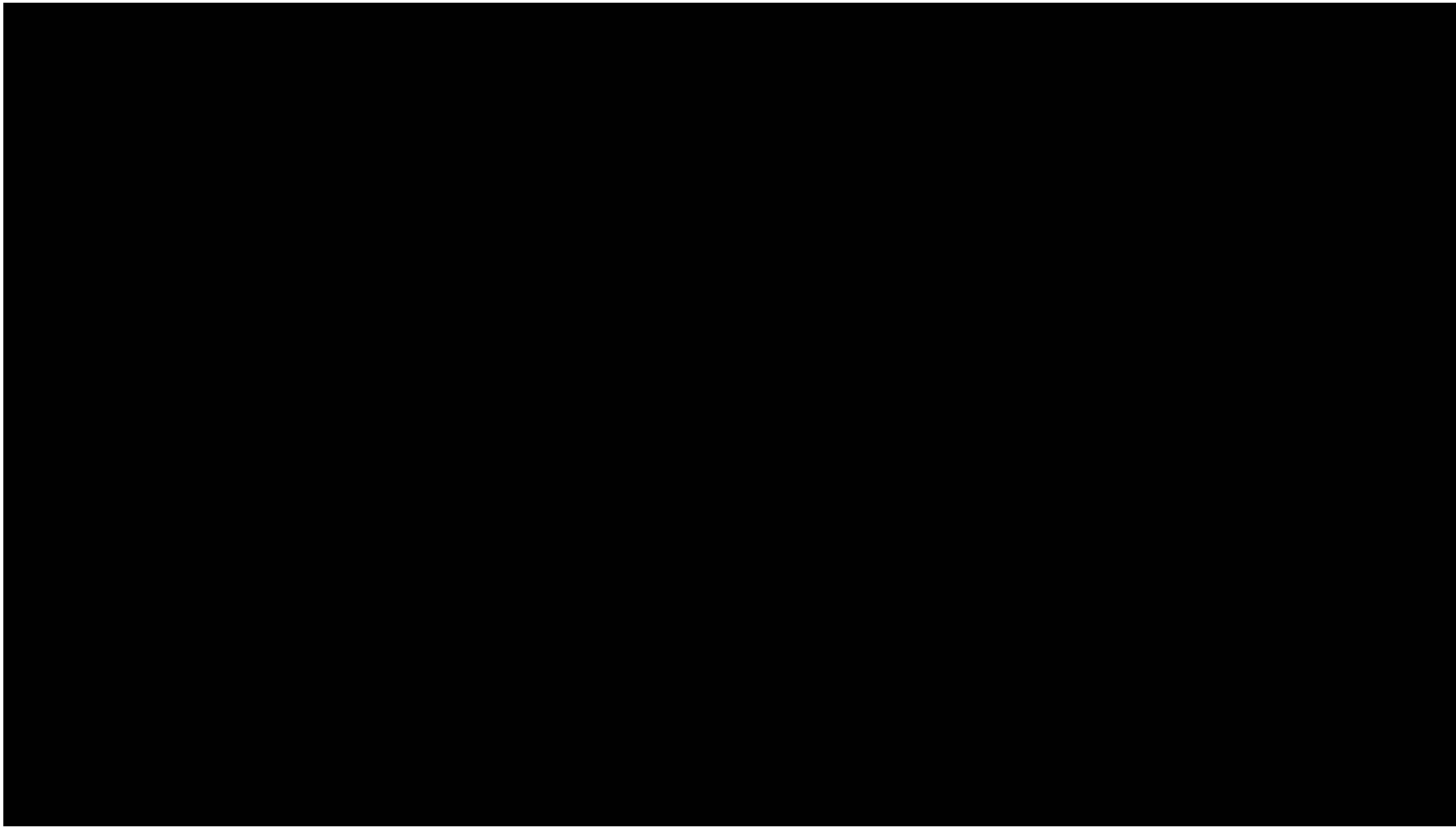
Earth's Magnetosphere





Atmospheric Response

Geomagnetic Storms and the Aurora

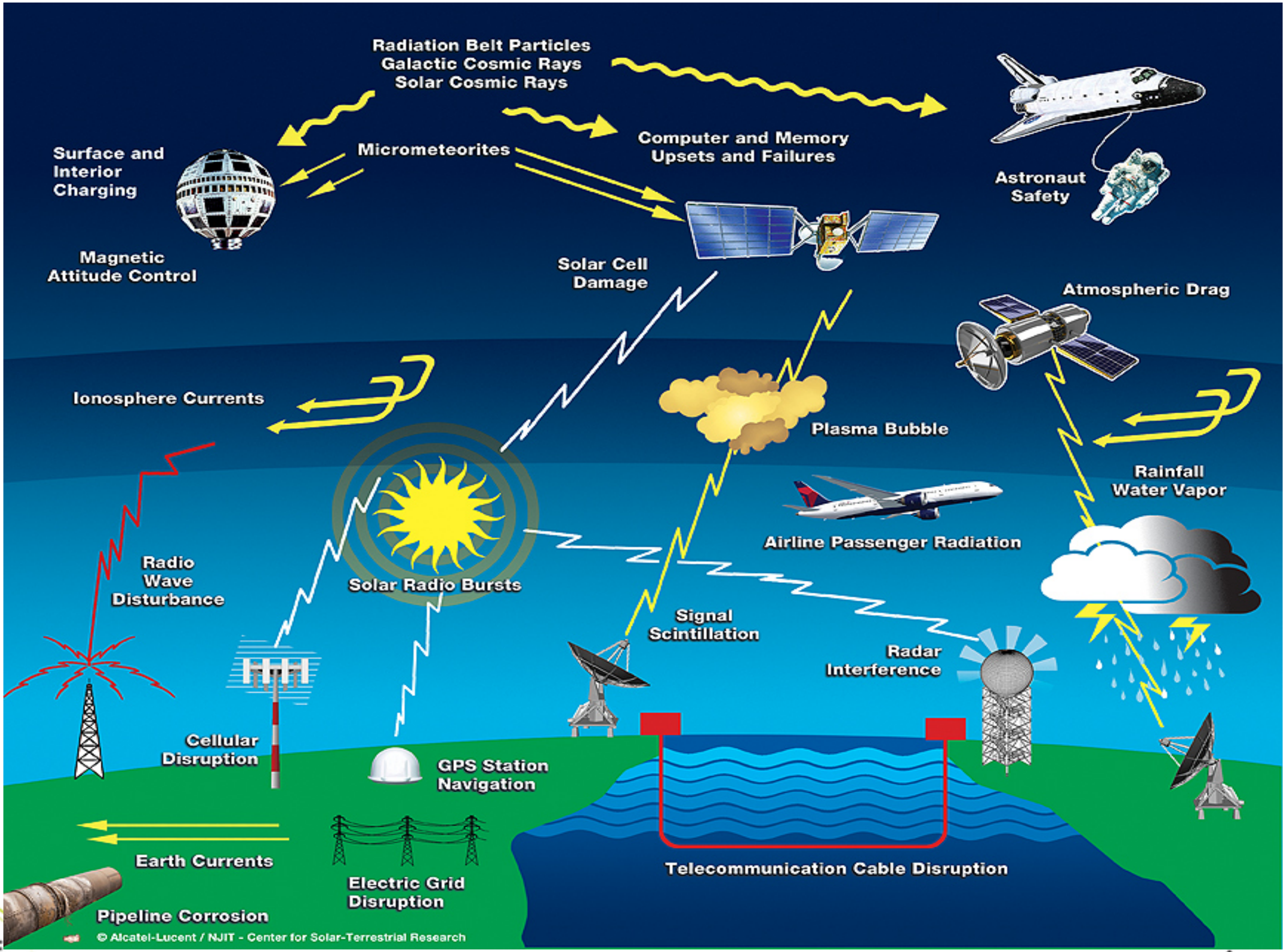


March 12, 2012 Abisko Park Northern Sweden

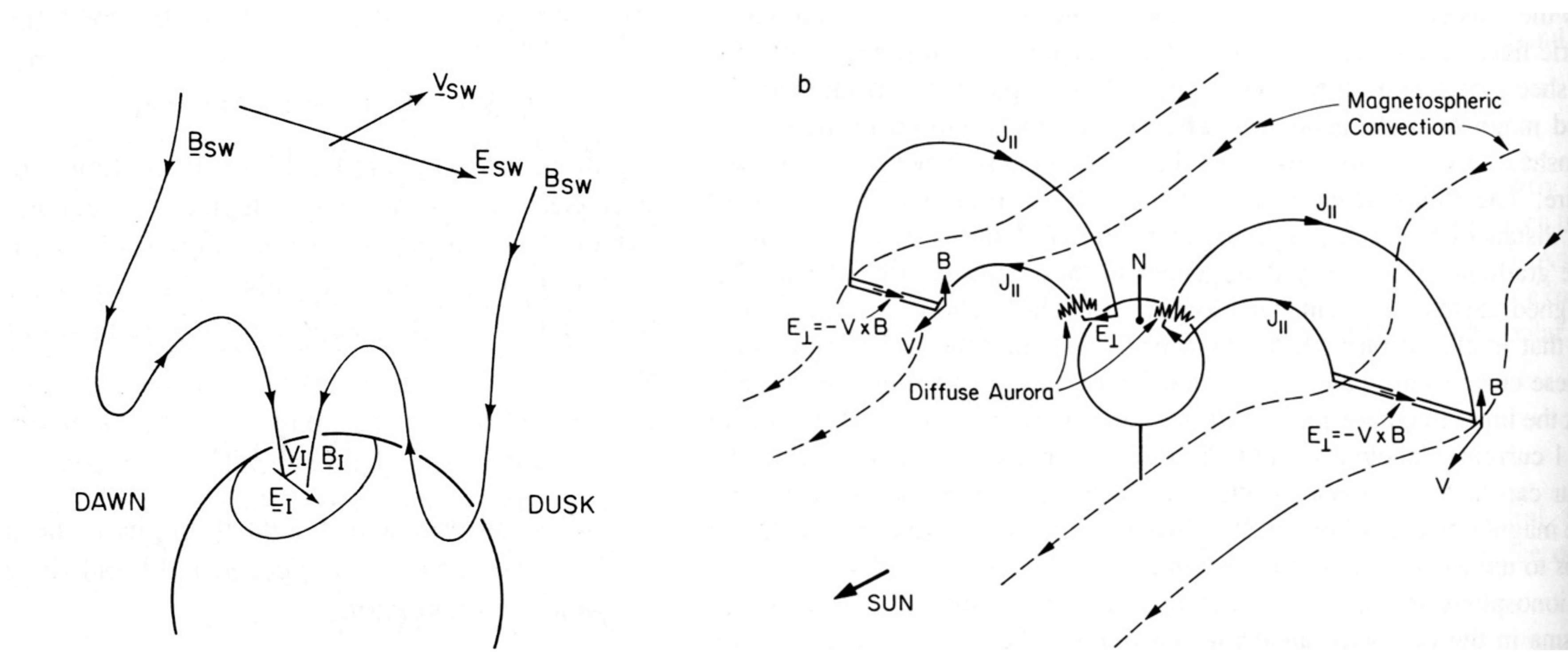
Aurora from High Altitude (ISS = 350 km)

September 2011 (Don Pettit, ISS Astronaut)

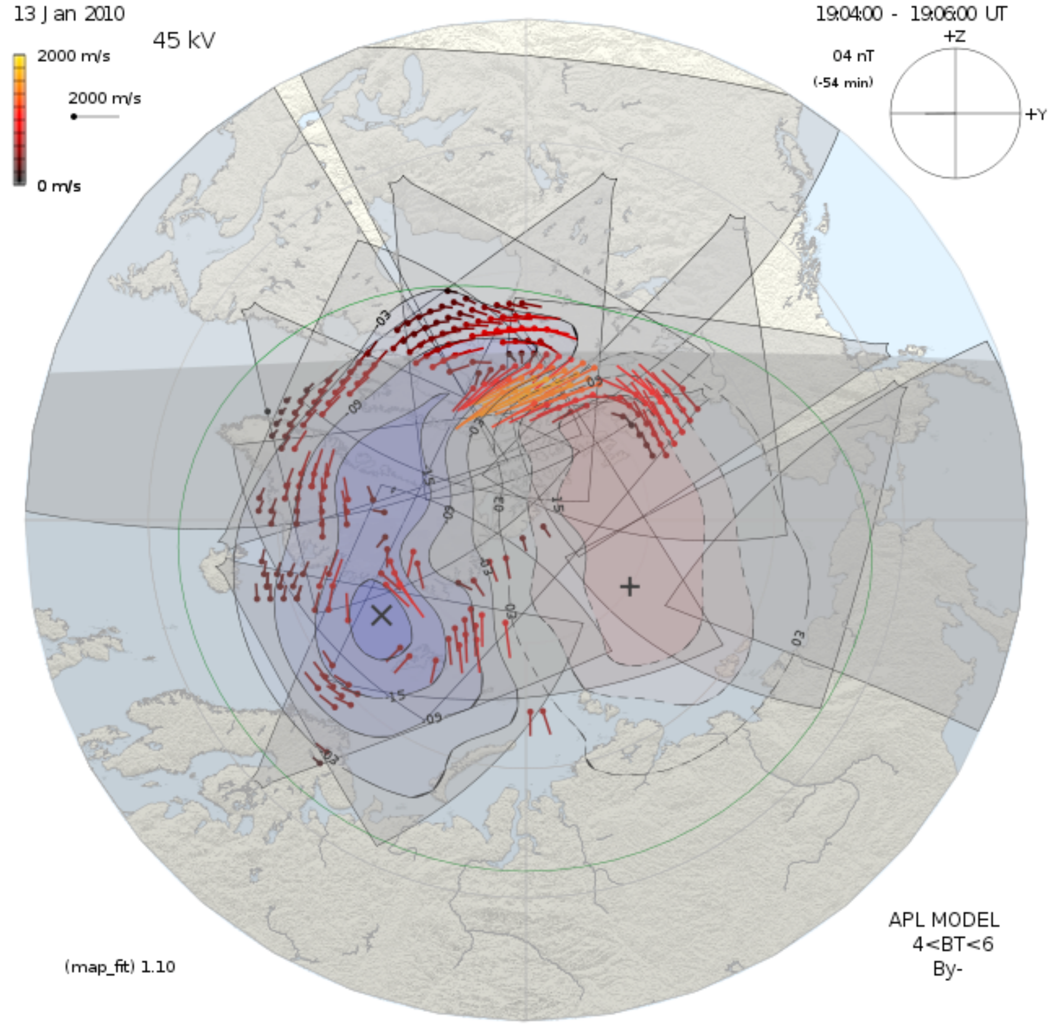
Space Weather Effects



Upper Atmosphere Circulation, Electrodynamically Powered by Solar Wind

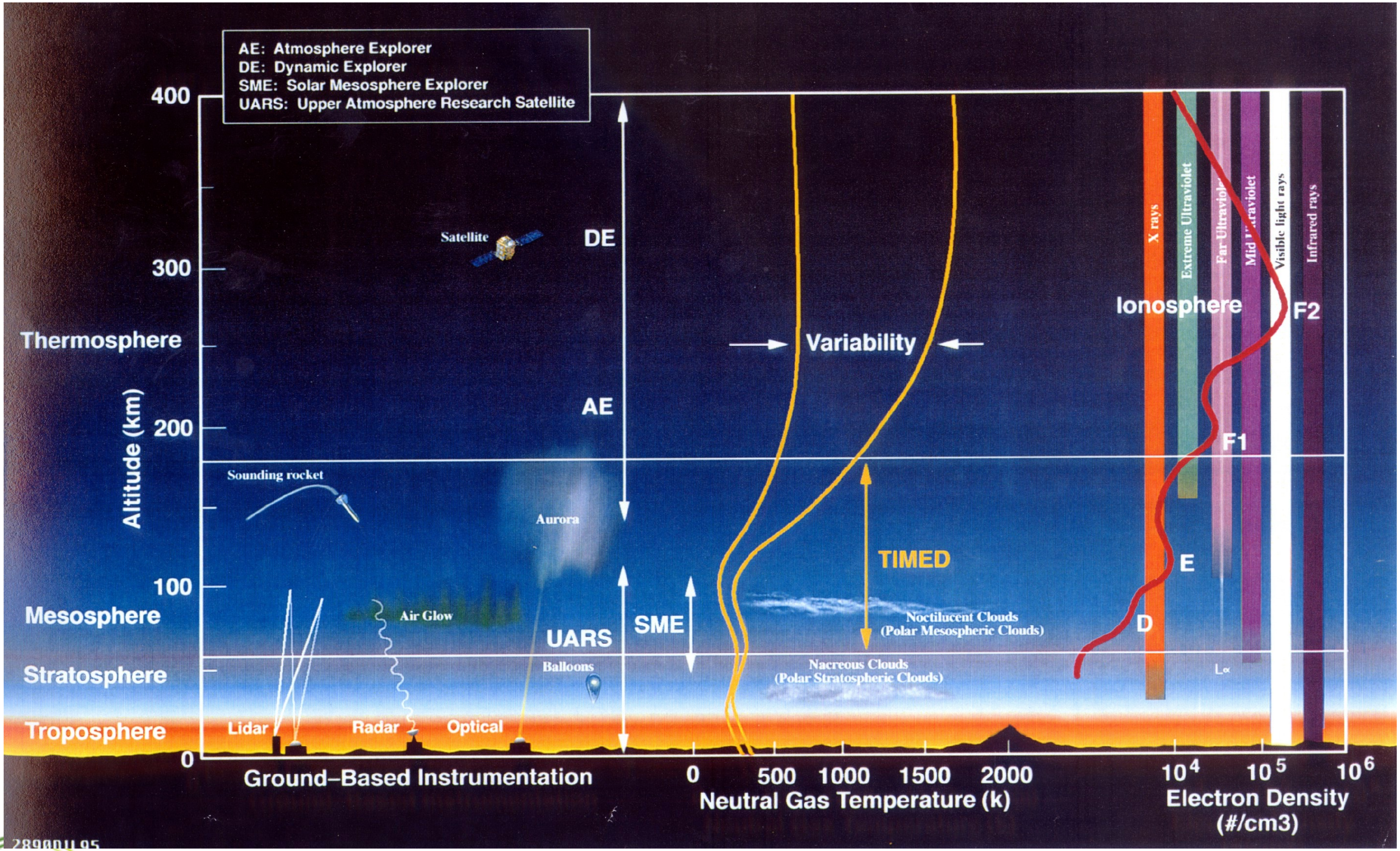


Upper Atmosphere Circulation



SuperDARN
HF Radar Scatter
Convection monitor

The Ionosphere and Thermosphere



Electrodynamics are Not Local, but Global

Circuit analogy:
Both ends of the magnetic field line matter

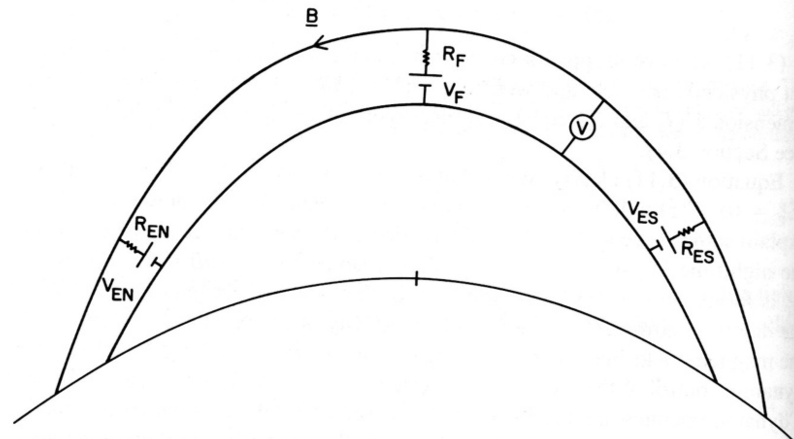
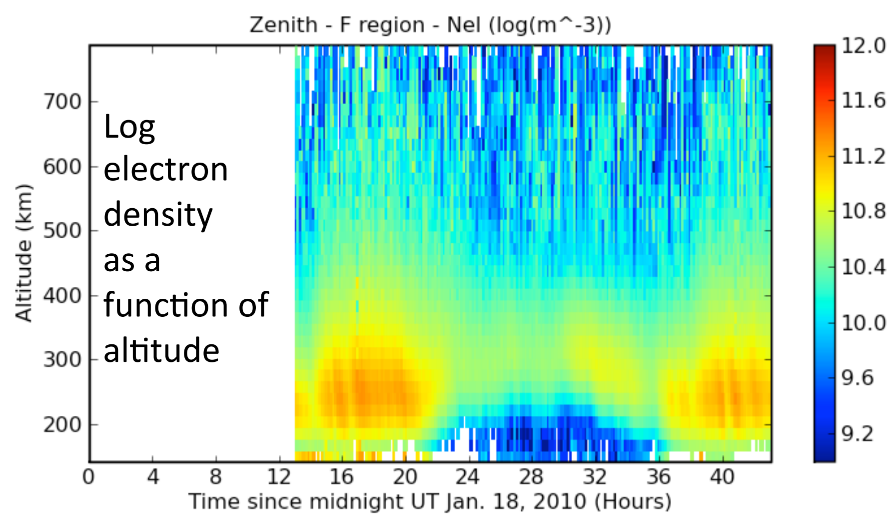


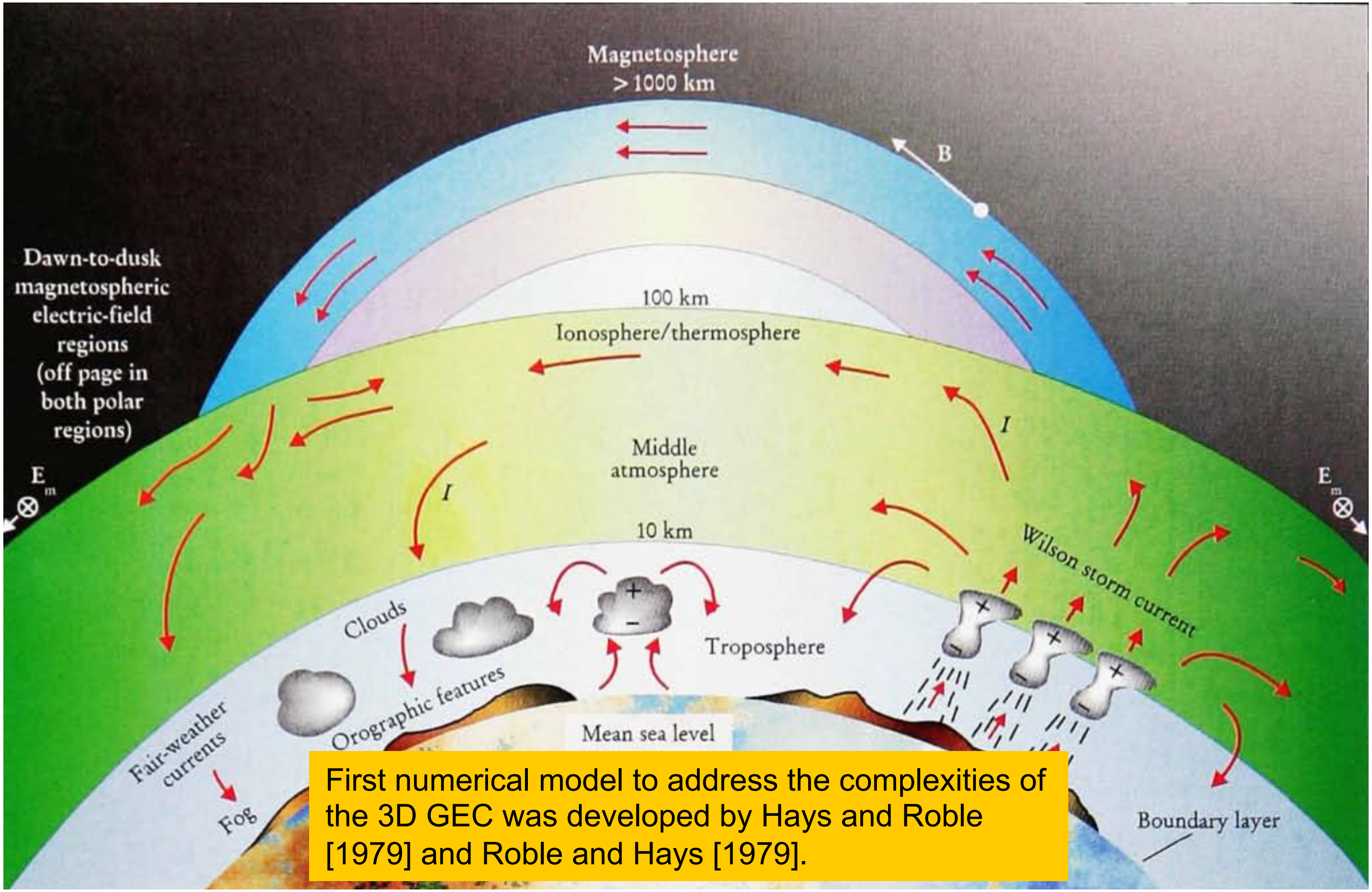
Fig. 3.10. Electric circuit analogy to the voltage sources in the equatorial F region. Off-equatorial E-region wind dynamo competes with the F-region dynamo at the equator to determine the voltage differences between magnetic field lines.

Conditions are very different day to night, seasonally, etc. etc.



The Global Electric Circuit

Courtesy J. Thayer, Frontiers in Earth System Dynamics project (UC Boulder)

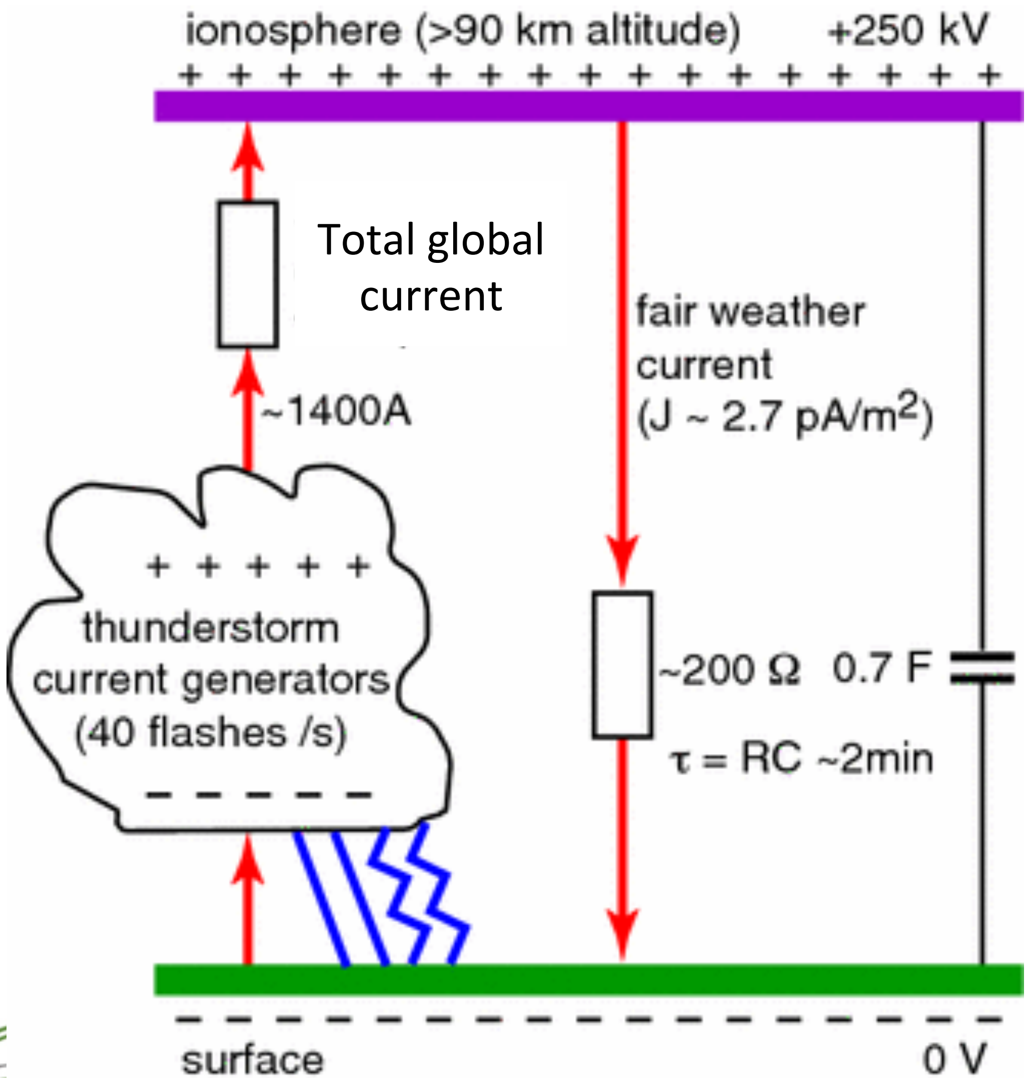


First numerical model to address the complexities of the 3D GEC was developed by Hays and Roble [1979] and Roble and Hays [1979].

Bering et al., Physics Today, 1998

Courtesy J. Thayer, Frontiers in Earth System Dynamics project (UC Boulder)

GEC Properties



The GEC involves many aspects of solar-terrestrial physics:

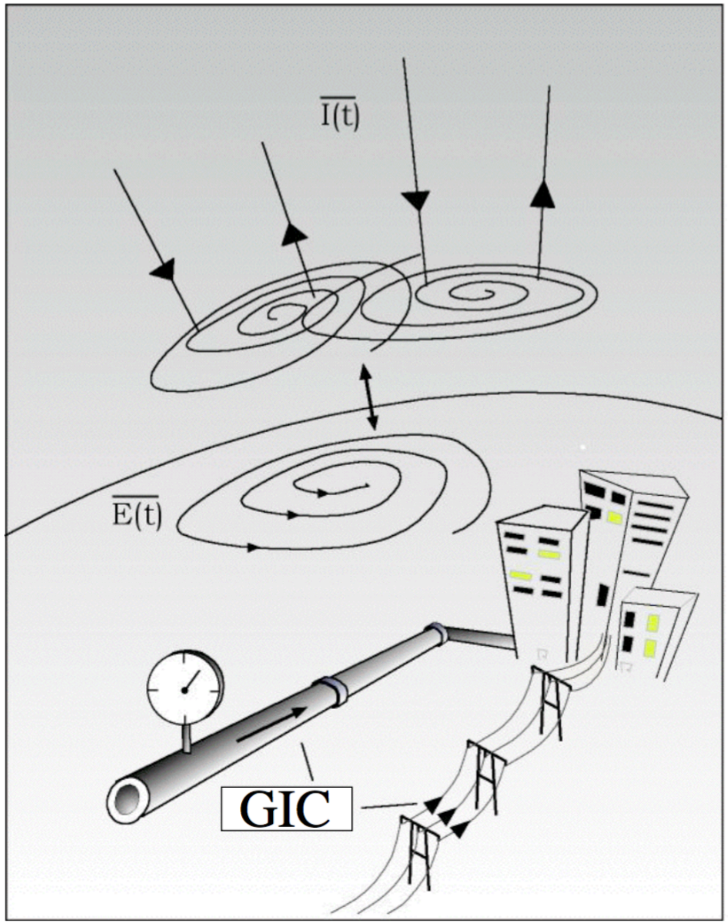
- Galactic cosmic rays
- Solar wind IMF
- Magnetospheric potentials and particles
- Ionosphere processes
- Radon emissions from solid earth
- Cloud formation and electrification
- Atmospheric aerosols
- Charge generation from oceans
- Atmospheric dynamics…

Vertical electric field at the surface: 100-300 V/m

Kirkby, Surv Geophys 2007

Geomagnetically Induced Currents (GICs)

Principle of GIC



Measure B(t) on the ground; compute dB/dt

Apply conductivity model to get horizontal E field

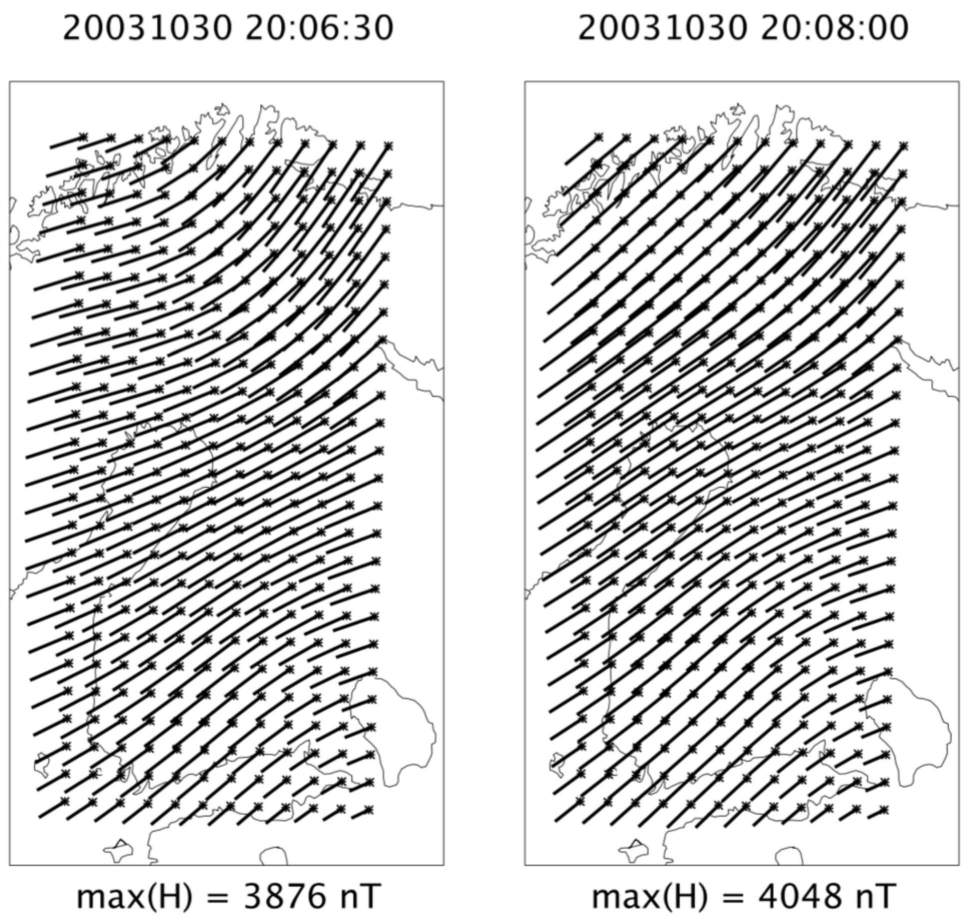
Apply DC description of power grid

Solve Ohm's law for driven currents in transformer neutrals and transmission lines

courtesy A. Viljanen, FMI

GIC Modeling Challenges

Magnetic field (ionospheric currents) varies smoothly between nearby time-steps.



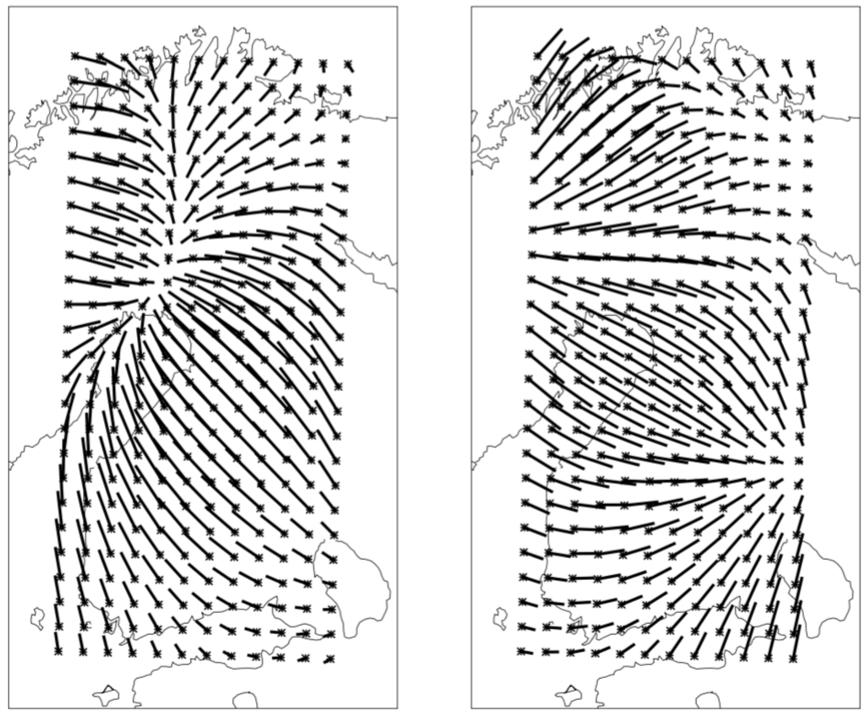
courtesy A. Viljanen, FMI

GIC Modeling Challenges

Dynamics ($d\mathbf{B}/dt$) is complex.

$$E_y(t) = -\frac{1}{\sqrt{\pi\mu_0\sigma}}\int_0^\infty \frac{dB_x(t-t')}{dt'}\frac{1}{\sqrt{t'}}dt'$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

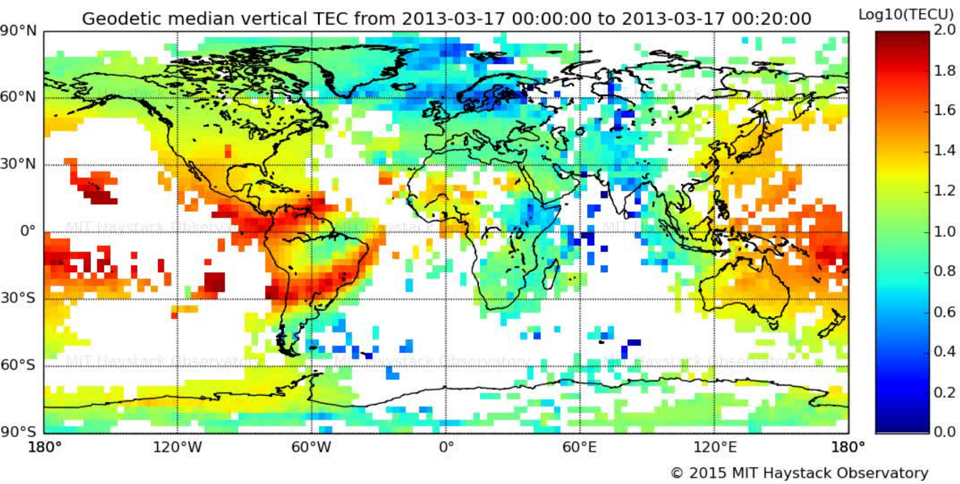


max(dH/dt) = 28.0 nT/s   max(dH/dt) = 13.4 nT/s

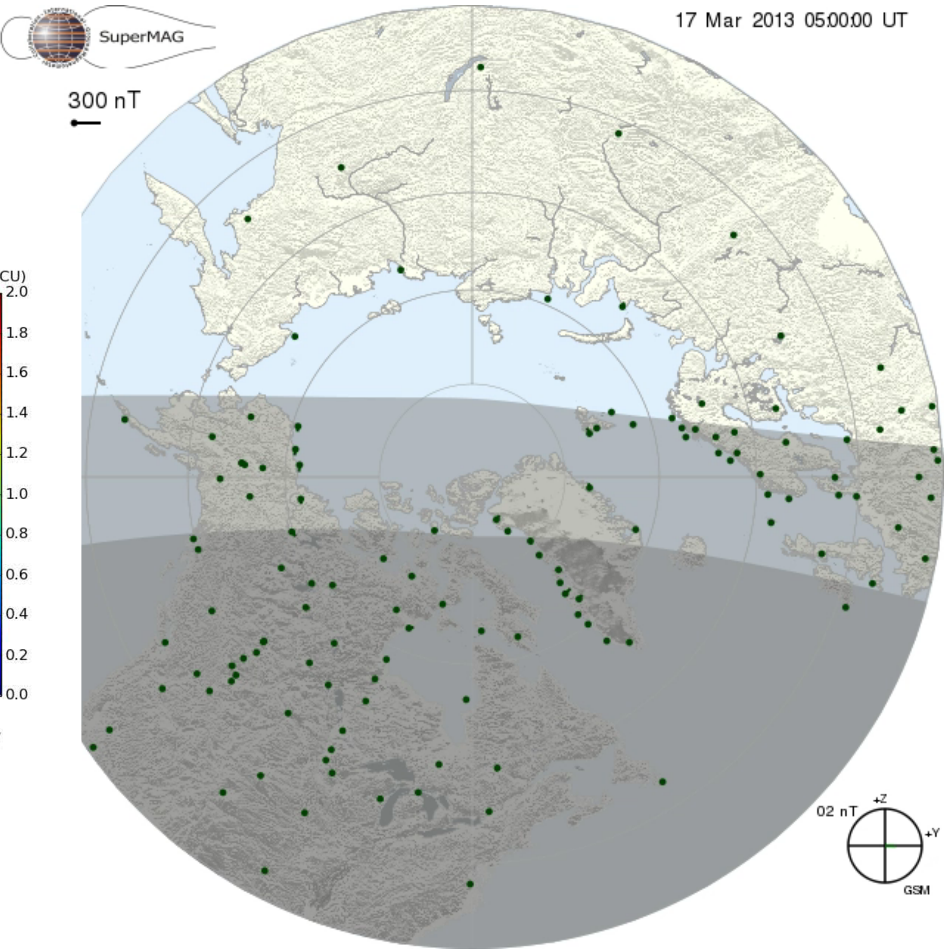
$d\mathbf{B}/dt$ "loses its memory" within a couple of minutes (*Pulkkinen et al.*, 2006)

courtesy A. Viljanen, FMI

Grids are Global, so Measurements Should Be Too

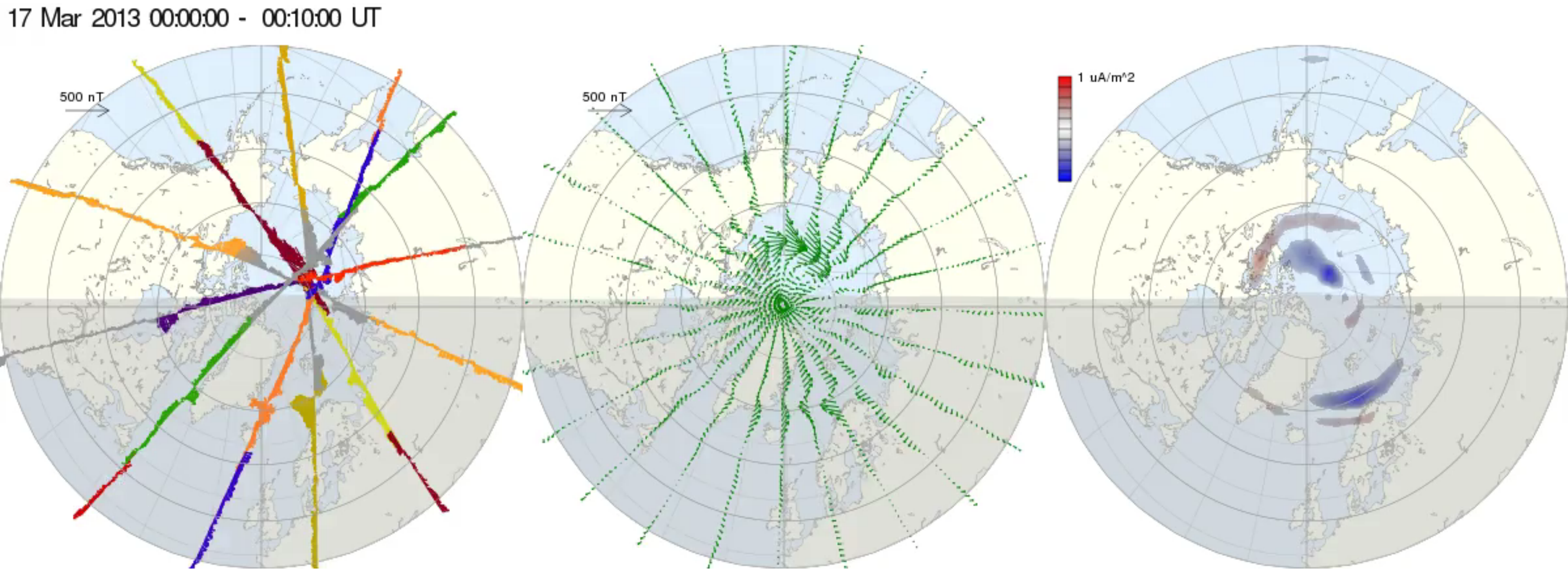


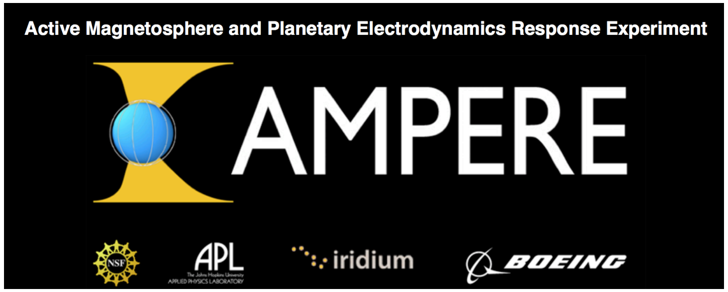
GPS derived global total electron content (MIT Haystack)



SuperMAG: Networks of Magnetometers

Space Based Measurements of B and J





Economics of Space Weather

SPACE WEATHER, VOL. 8, S09004, doi:10.1029/2009SW000498, 2010

THE BELL SYSTEM TECHNICAL JOURNAL
Vol. 53, No. 9, November 1974
Printed in U.S.A.

Outage of the L4 System and the Geomagnetic Disturbances of 4 August 1972

4 August 1972:
AT&T L4 cable Chicago to San Francisco

SPACE WEATHER, VOL. 10, S04003, doi:10.1029/2011SW000750, 2012

Generation of 100-year geomagnetically induced current scenarios

A. Pulkkinen,[1,2] E. Bernabeu,[3] J. Eichner,[4] C. Beggan,[5] and A. W. P. Thomson[5]
Received 15 November 2011; revised 21 February 2012; accepted 22 February 2012; published 24 April 2012.

SPACE WEATHER, VOL. 4, S10004, doi:10.1029/2006SW000234, 2006

Recordings of geomagnetically induced currents and a nowcasting service of the Finnish natural gas pipeline system

A. Viljanen,[1] A. Pulkkinen,[2,3] R. Pirjola,[4,5] K. Pajunpää,[1] P. Posio,[1] and A. Koistinen[1]
Received 21 March 2006; revised 23 May 2006; accepted 25 May 2006; published 20 October 2006.

An anatomy of space weather's electricity market impact: Case of the PJM power grid and the performance of its 500 kV transformers

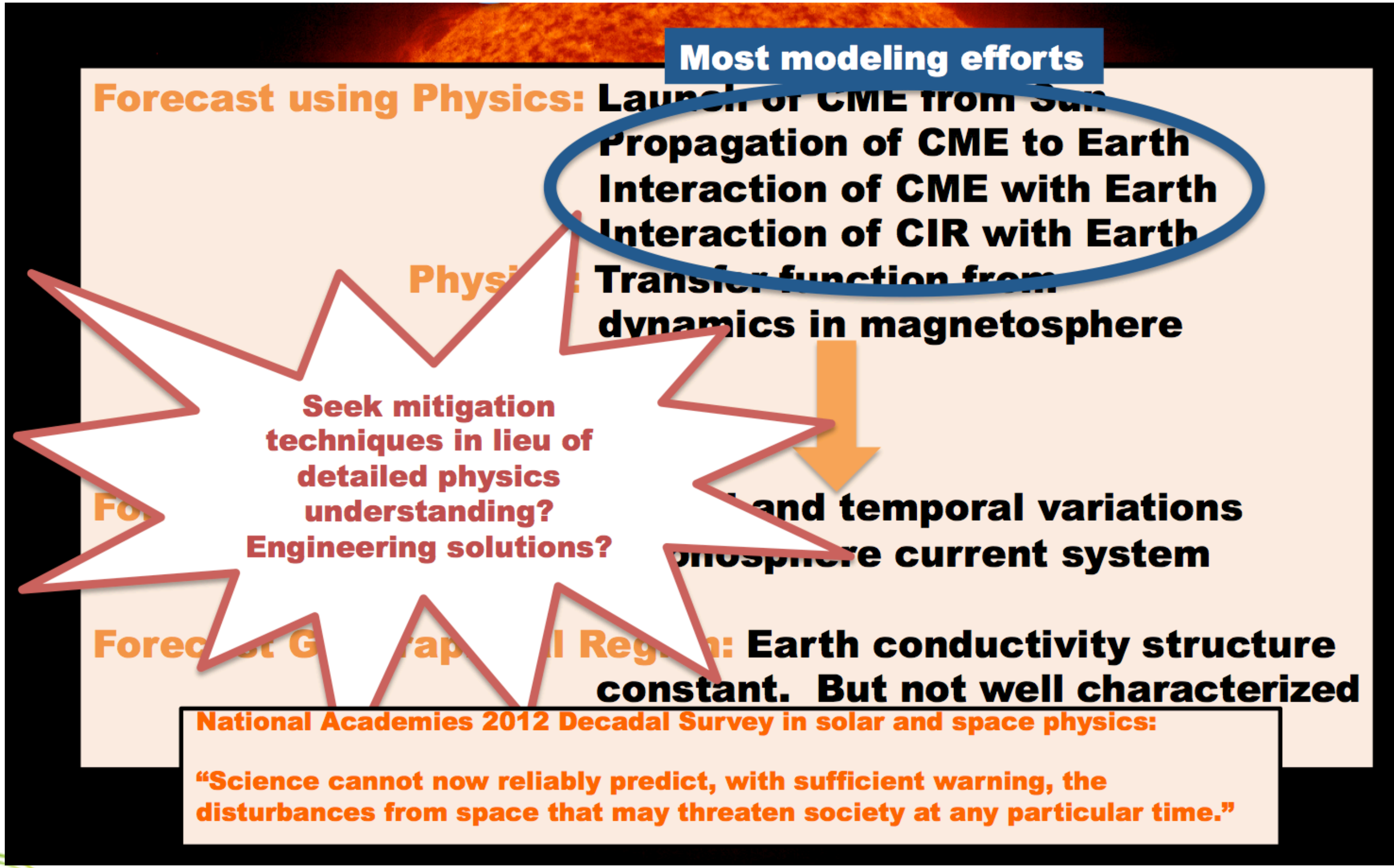
Kevin F. Forbes[1] and O. C. St. Cyr[2,3]
Received 16 May 2009; revised 18 April 2010; accepted 22 April 2010; published 30 September 2010.

PJM Perspectives (2015)
DO: reduce west-east transfers if GIC > 10 amps at detection station
DO: raise voltages and anticipate reactive asset loss during storms
DO NOT: be concerned with transmission congestion by geomagnetic activity
(Congestion loss ~$918M 1st 6 months 2015; PJM billings ~$50B/year)

Unremarked upon: Potential degradation of transformer oils by cumulative space weather events.

The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

Prediction or Mitigation?



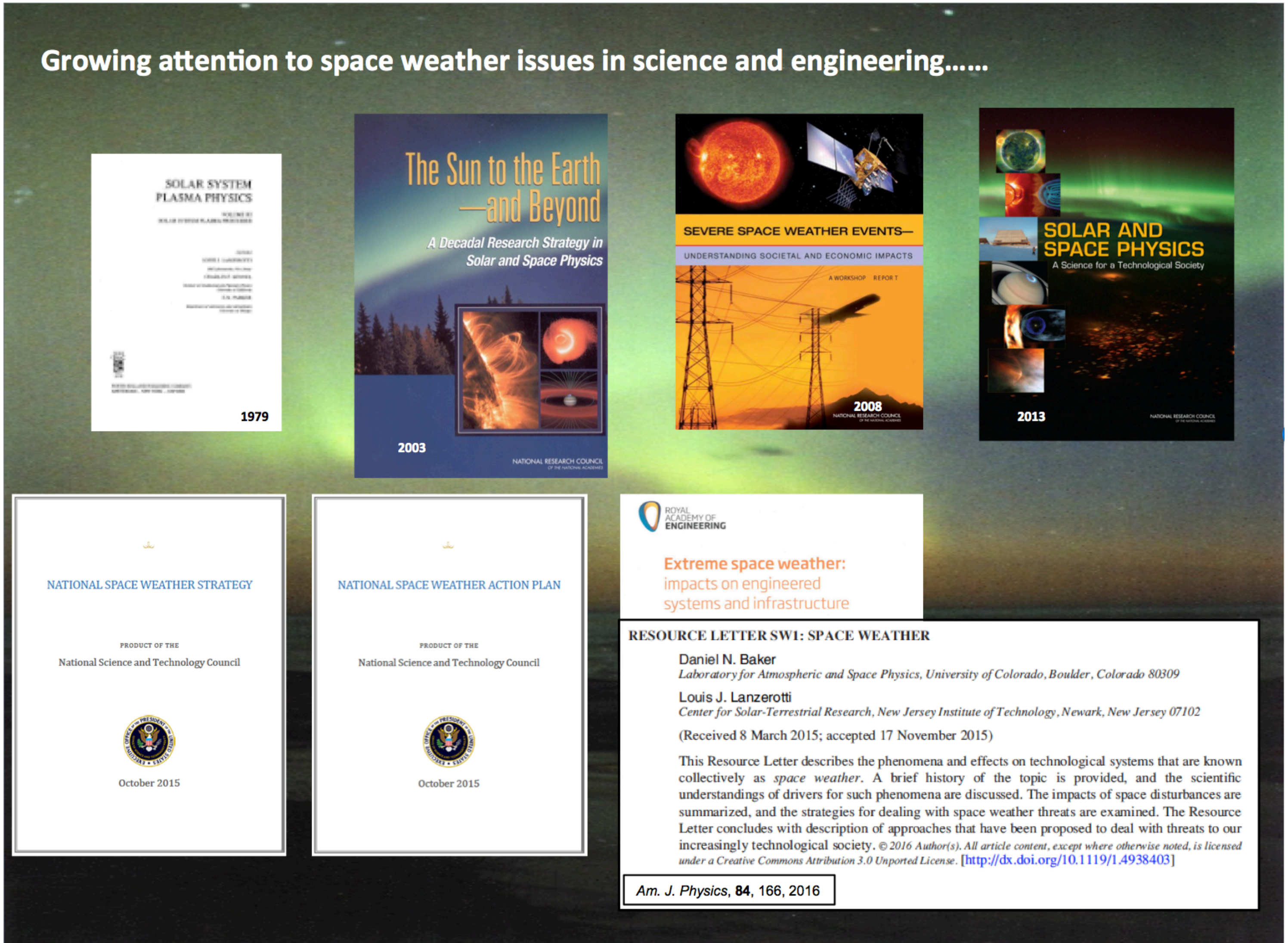
IEEE PES Power & Energy Society®

IEEE

In Any Case…

Heliophysics is key both to basic understanding and to national space weather preparedness.

Reference Article



Thanks for Your Attention!