Space Weather Super-Storm
Not *IF* but *WHEN*
And
Extreme Solar Minimum

Image: K. Turnbull/J. Wild/ESA.

Presentation to
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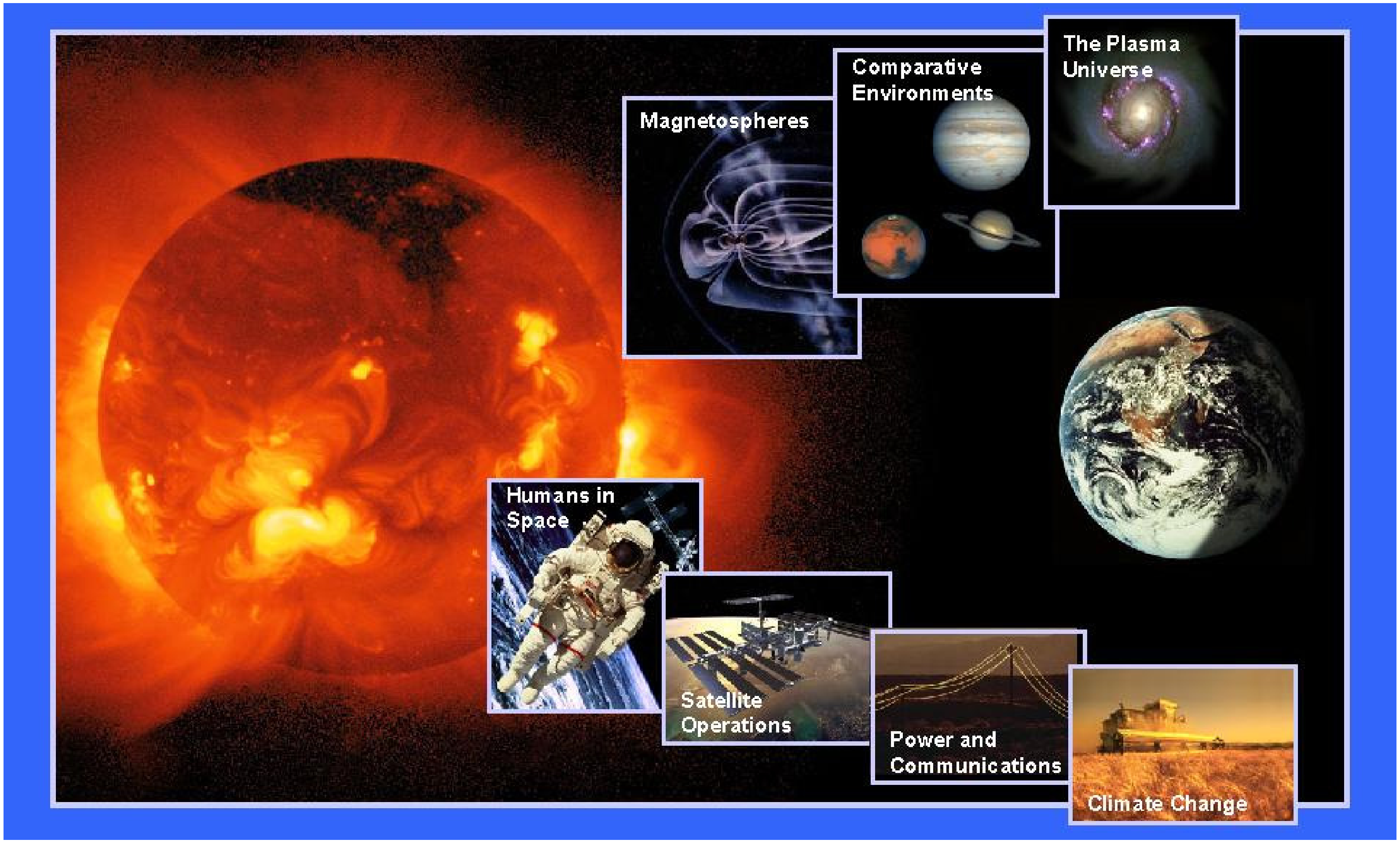
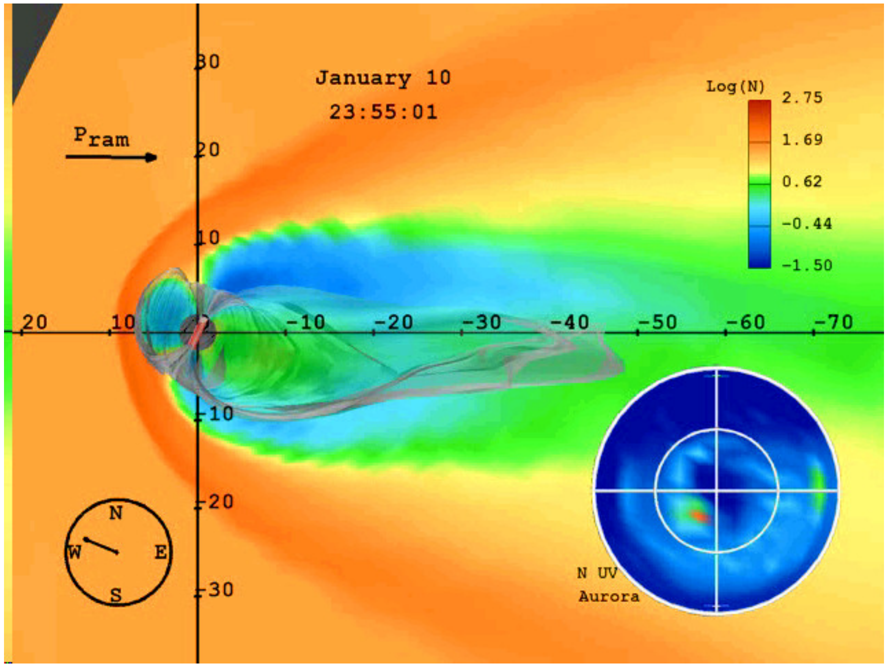
Understanding Sun-Earth/Planet Connections



What is Space Weather?

- **SPACE WEATHER refers to conditions on the Sun and in the solar wind, magnetosphere, ionosphere, and thermosphere that can disrupt modern technologies and affect human life or health.**
- **"Space Weather" effects on installations on Earth not a new phenomena**
- 17 November 1848: Telegraph wire between Pisa and Florence Interrupted
- September 1851: Telegraph wire in New England disrupted
- Induced currents made it possible to run the telegraph lines without batteries.

Like weather on Earth, Space Weather comes in different forms and different strengths. However, SWx is governed by an 11-year cycle that allows us to predict, at some level, when effects are likely to be most severe. This period is called "Solar Maximum" and is next likely to occur between 201-2015.

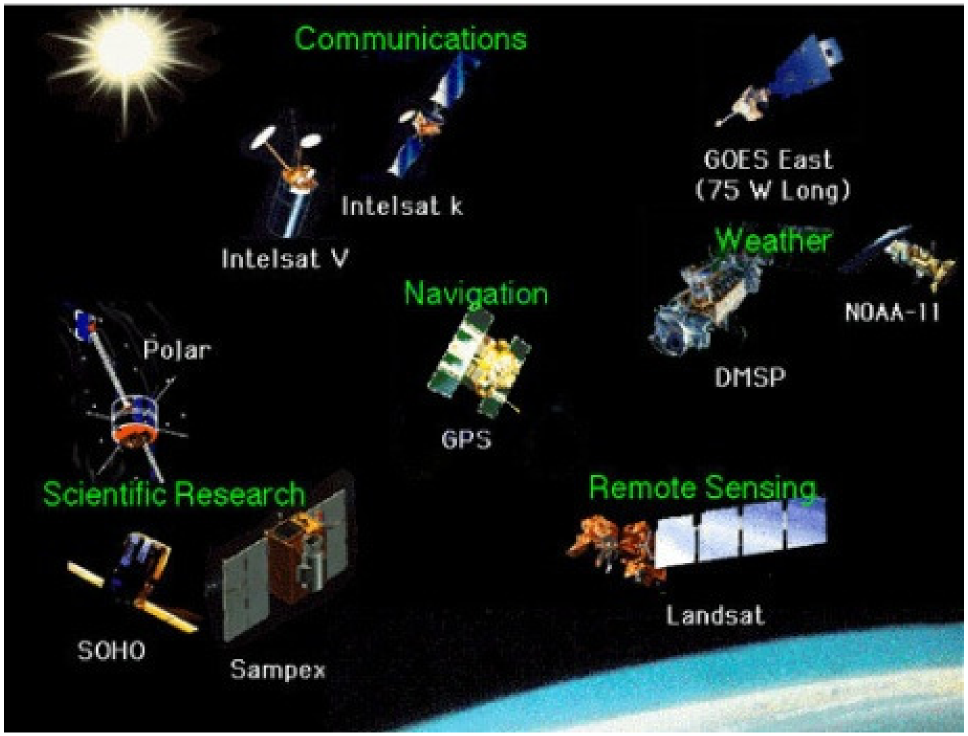


Space Weather: Why should we care?

The growth of technologies have left society more at risk from space weather

The first example of the impact of space weather on technology was the electric telegraph, arguably the Victorian equivalent of the internet. This was followed by the telephone at the end of the 19th century and radio communications in the early part of the 20th century. Since the 1950s there has been a steady growth in the use of advanced technologies by business and government.

- **The most rapidly growing sector of the communication market is satellite based**
  - **Broadcast TV/Radio,**
  - **Long-distance telephone service, Cell phones, Pagers**
  - **Internet, finance transactions**
  - **Hundreds of millions of users of GPS**

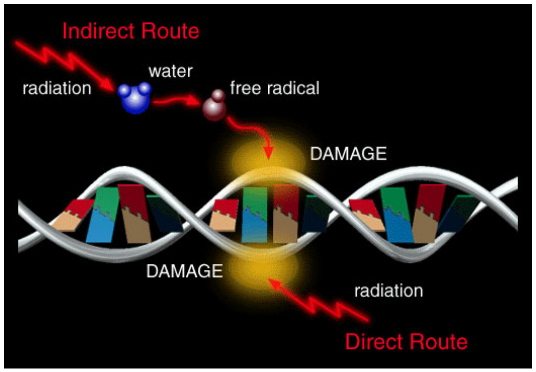


- **Change in technology**
  - **more sensitive payloads**
  - **high performance components**
  - **lightweight and low cost**

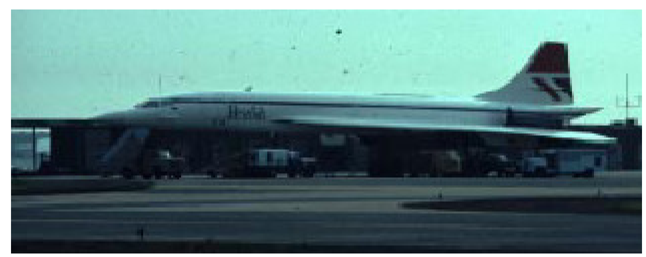
Space Weather warning will be very important for our society in the future.

Damages: estimated to 200 M$ per year
  - **100 M$ - satellites**
  - **100 M$ - powergrids**
  - **10 M$ - communication**

Space Weather: Why should we care?



- **Humans in space**
  - Space Shuttle, International Space Station, missions to Moon, Mars & Beyond



- **Crew/Passengers in high-flying jets and polar routes**
  - Concorde carries radiation detectors
  - Passengers may receive radiation doses equivalent to several chest X rays.

High Energy Particles Hazards to Humans

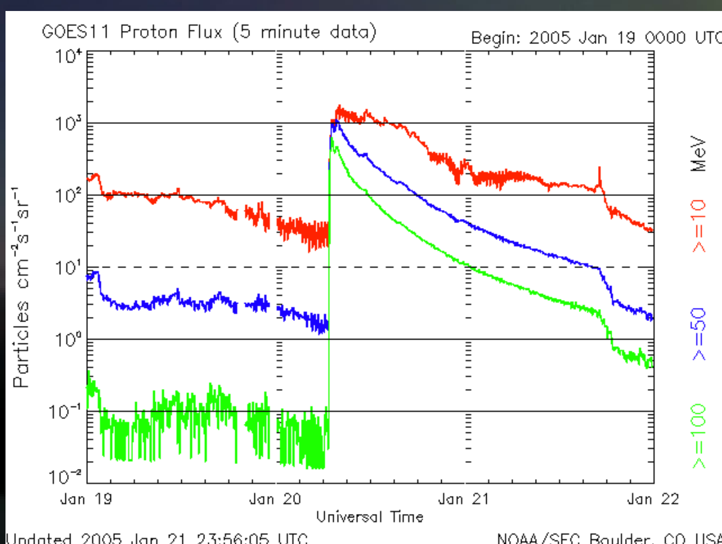
Space Weather: Implications for Business

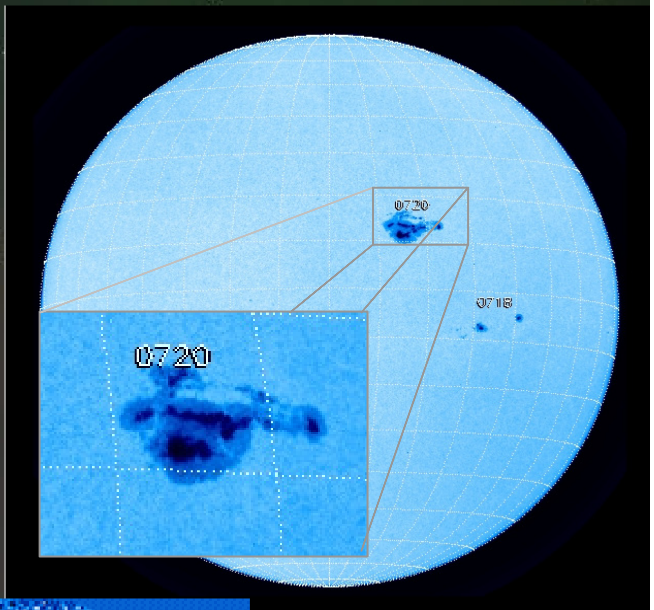
- **Space Weather could Potentially create huge disturbances in the transport, aviation and power sectors**
- **All GPS signals are vulnerable to space weather, which impacts on, for example aviation navigation systems**
- **Space weather can also disrupt pipelines and railway signals**
- **A very severe outbreak of space weather could create a systemic risk to society**
- **Business at risk from space weather need access to relevant expertise**
- **Finding defences against Space weather may also provide business opportunities**

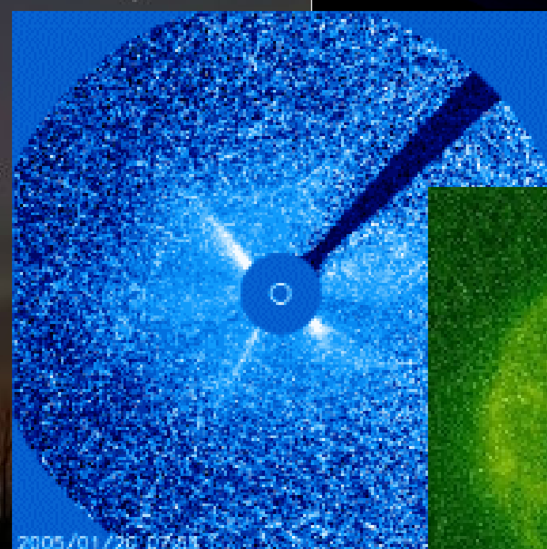
January 20, 2005 – Region 720 Produces Powerful Radiation Storm

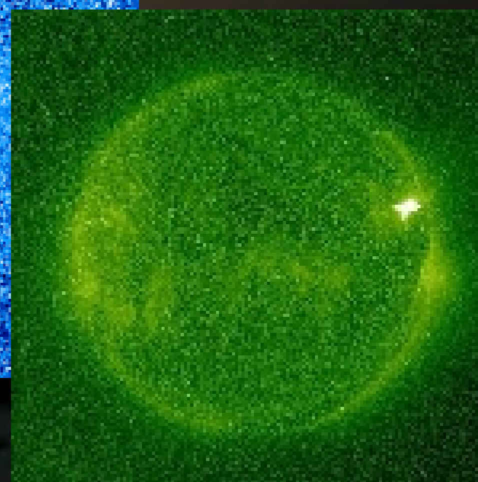
The X7 flare on 20 January 2005 was associated with the most highly energetic radiation storm of Solar Cycle 23. The $\geq$100 MeV protons reached 652 pfu, making it the strongest $\geq$100 MeV event of the last cycle and the strongest since Oct 1989 (680 pfu).

This storm was short-lived, but did exceed the FAA Solar Radiation Alert at Flight Altitudes for about 1.5 hours.









So What Do We Mean by Extreme SWx?

From Cliver & Svaalgard (Solar Physics, 2004)

The biggest geomagnetic storm occurred in March 1989.

The biggest solar particle event occurred in Sept. 1859.

The lowest latitude auroras were observed in Feb. 1872.

The fastest CME on record crossed the sun-Earth divide in only 14 hours in August 1972.

The most intense SID occurred during the Halloween storms of 2003.

Solar Flares – EMP from the Sun

Corresponding NOAA space weather scale: Radio Blackout

Extreme (R5) = X20

Frequency: Happens less than once per cycle.

Consequence: Complete HF radio blackout on the entire sunlit side of the Earth lasting for a number of hours, loss of HF contact with mariners and aviators.

Other effects: Direct radio interference with GPS signals. Accelerated orbital decay of satellites.

Strongest X-ray Flares since 1976

1. November 4, 2003 X28+
2. April 2, 2001 X20.0
3. August 16, 1989 X20.0
4. October 28, 2003 X17.2
5. September 7, 2005 X17
6. March 6, 1989 X15.0
7. July 11, 1978 X15.0
8. April 15, 2001 X14.4
9. April 24, 1984 X13.0
10. October 19, 1989 X13.0

SOURCE: IPS Radio & Space Services and Spaceweather.com

Geomagnetic Storms

Corresponding NOAA Space Weather Scale: Geomagnetic Storm

Extreme (G5) = K9

All of the top storms saturate the K-index scale at K9.

Frequency: 4 per cycle

Consequences: low-latitude auroras, transformer damage, power outages , pipeline currents reach hundreds of amps

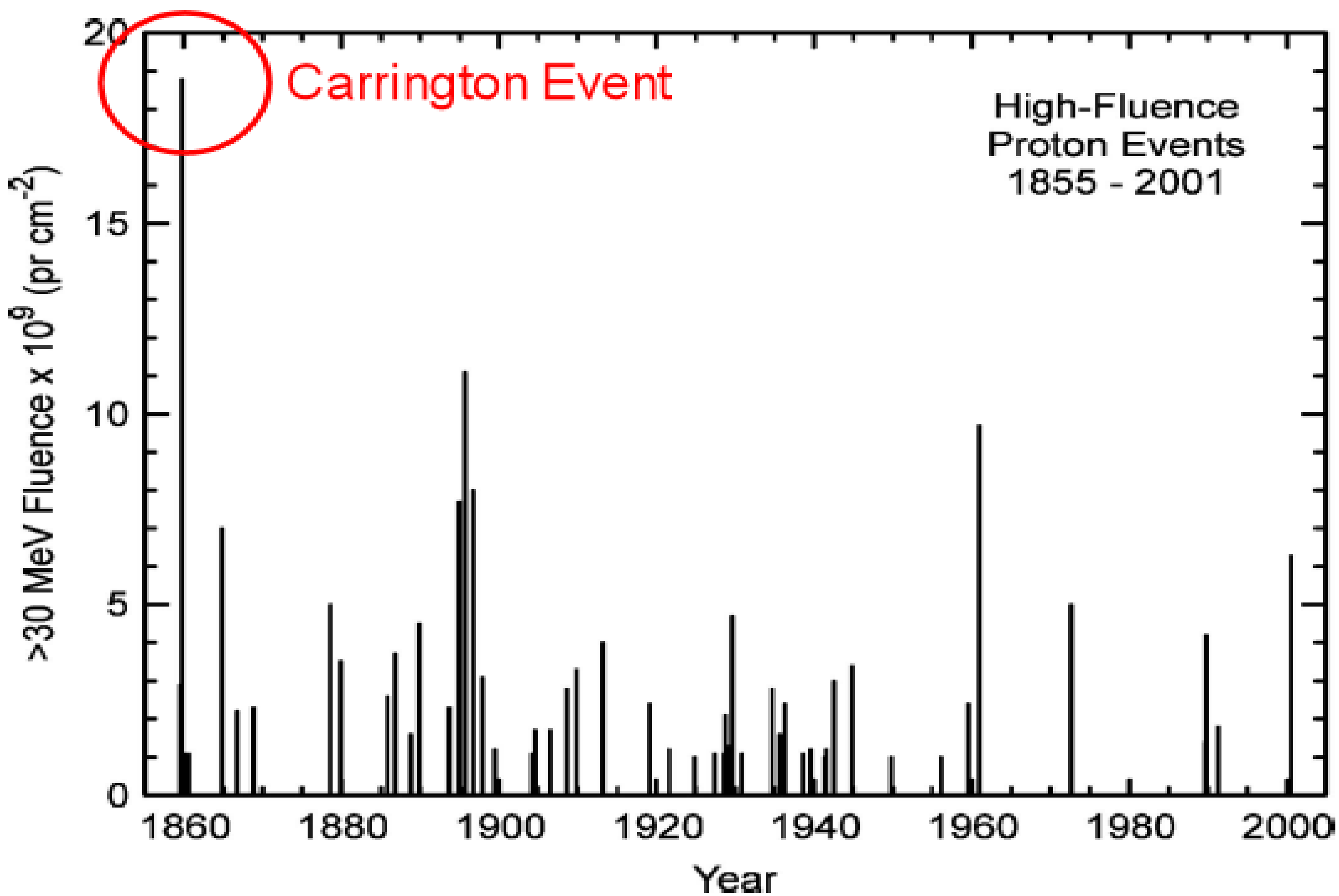
Top Geomagnetic Storms 1932-2000 (Dst)

1. March 14, 1989 -548 nT
2. July 5, 1941 -453 nT
3. March 28, 1946-440 nT
4. July 15, 1959 -434 nT
5. February 11, 1958 -428 nT
6. September 13, 1957 -426 nT
7. May 26, 1967 -391 nT
8. March 31, 2001-383 nT
9. March 1, 1941 -382 nT
10. November 9, 1991 -375 nT

"[Several lines of evidence suggest] the Carrington storm ranks among, but not significantly beyond, the greatest storms observed since." – Cliver and Svalgaard (2004)

Solar Energetic Particles – A Hail of a Problem

SEPs are subatomic particles (mostly protons) accelerated to almost-light speed by explosions on the sun and subsequent shock waves. They pepper spacecraft and Earth's upper atmosphere like a cosmic hailstorm. In this category, the Carrington event is ~twice as strong as any other event of the past 150 years.



Solar Energetic Particles – A Hail of a Problem

NOAA Space Weather Scale:
Solar Radiation Storm

Extreme (S5) = 10,000*

Frequency: Happens less than once per cycle on average, but more often recently.

Consequences: Radiation hazard to astronauts on EVA and people in high-flying aircraft at high latitudes; some satellites rendered useless; complete blackout of HF communications in polar regions.

Top Solar Proton Events since 1976

Based on data from the NOAA Space Weather Prediction Center

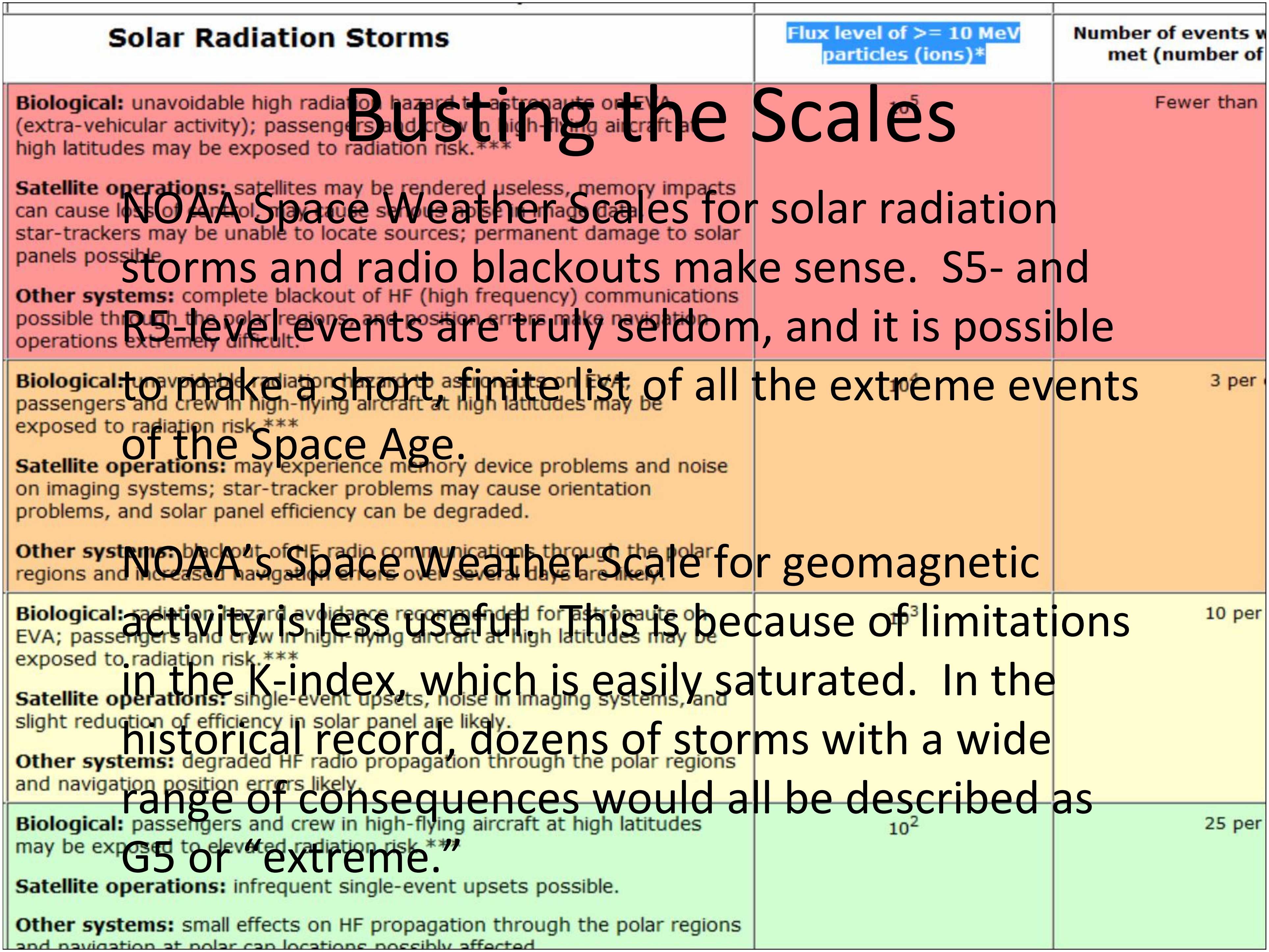
1. March 23-34, 1991	43,000 (X9)
2. Oct. 19-20, 1989	40,000 (X13)
3. Nov. 4-6, 2001	31,700 (X1)
4. Oct. 28-29, 2003	29,500 (X17)
5. July 14-15, 2000	24,000 (X5)
6. Nov. 22-24, 2001	18,900 (M9)
7. Nov. 8-9, 2000	14,800 (M7)
8. Sep. 24-45, 2001	12,900 (X2)
9. Feb. 20-21, 1994	10,000 (M4)

*Flux level of >= 10 MeV particles

Busting the Scales

NOAA Space Weather Scales for solar radiation storms and radio blackouts make sense. S5- and R5-level events are truly seldom, and it is possible to make a short, finite list of all the extreme events of the Space Age.

NOAA's Space Weather Scale for geomagnetic activity is less useful. This is because of limitations in the K-index, which is easily saturated. In the historical record, dozens of storms with a wide range of consequences would all be described as G5 or "extreme."



What Makes the Carrington Event Special?

Other solar storms have exceeded the Carrington Event in narrow categories: geomagnetic intensity, X-ray flare power, the spread of auroras, and so on. The Carrington Event is special because it is near the top of all categories at once.

But Wait…There’s More: 1859 Carrington Event

- **Three days of intense aurora below 50 degrees latitude**
  - **As far south as 10 degrees latitude**
- **Significant portions of the world’s telegraph lines were adversely affected**
  - **Telegraph rooms caught fire**
  - **Some stations were out of operation for eight hours**
- **The largest solar particle event on record**
  - **From Ice Core data covering over 500 years**
  - **May have reduced ozone by 5 percent for 4 years**

While the 1859 event has close rivals or superiors in each of the above [five] categories of space weather activity, it is the only documented event of the last ~150 years that appears at or near the top of all of the lists.

THE 1859 SOLAR–TERRESTRIAL DISTURBANCE
AND THE CURRENT LIMITS OF
EXTREME SPACE WEATHER ACTIVITY,
E. W. CLIVER and L. SVALGAARD
Solar Physics (2004) 224: 407–422

Infrequent but large solar/stellar flares (early impressions based on Kepler data by Karel Schryver)

- Very large flares, easily seen in the broad-band observations against the photospheric emission are commonly observed in the large stellar sample. And that energies for such events easily reach from 1,000 to 100,000 times that of an X1 solar flare.
- These are for stars that appear to have rotation periods of order 10-20 days, as the Sun did at about 1/4 to 1/2 its present age, and for stars a little cooler than the Sun, but otherwise similar.
- Clearly, huge flares do occur on Sun-like stars, but we have yet to establish if this is a property of active (young) stars only or whether the Sun can still do this, albeit infrequently.
- Stellar observations and solar signatures embedded in ice cores might hold information on this.

Estimated Impacts

According to a study by the Metatech Corporation, the occurrence today of an event like the May 1921 superstorm, [*less intense than the Carrington Event*] would result in large-scale blackouts affecting more than 130 million people and **would expose more than 350 transformers to the risk of permanent damage**.

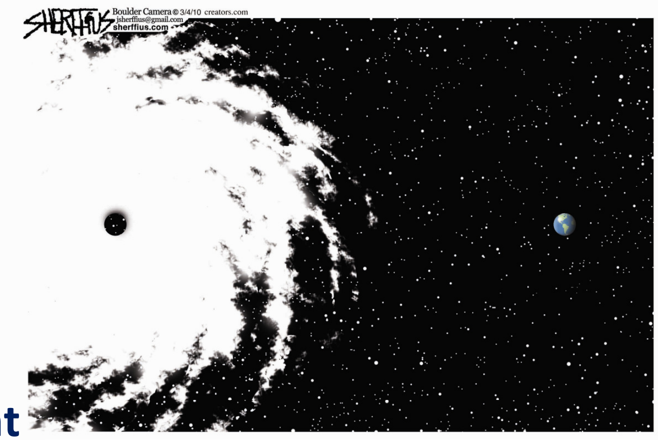
NRC Workshop Report, 2008

Transformers in general are "one-of-a-kind" design, take months to build, and would take months to replace

Most Emergency Power system backups rely on gasoline or other fuel, and reserves-on-hand are limited to a few days at best

The Doomsday Scenario

How credible is it?



The next major solar storm could be a global Katrina - News Item.

IT IS midnight on 22 September 2012 and the skies above Manhattan are filled with a flickering curtain of colourful light. Few New Yorkers have seen the aurora this far south but their fascination is short-lived. Within a few seconds, electric bulbs dim and flicker, then become unusually bright for a fleeting moment. Then all the lights in the state go out. Within 90 seconds, the entire eastern half of the US is without power.

A year later and millions of Americans are dead and the nation's infrastructure lies in tatters. The World Bank declares America a developing nation. Europe, Scandinavia, China and Japan are also struggling to recover from the same fateful event - a violent storm, 150 million kilometres away on the surface of the sun.

New Scientist "Space storm alert: 90 seconds from catastrophe
23 March 2009 by Michael Brooks

***http://www.newscientist.com/article/mg20127001.300-space-storm-alert-90-seconds-from-catastrophe.html**

upper illustration: John Sherffius, Boulder Camera, 3/5/10

Lower illustration: http://www.history.com/shows/life-after-people/photos/

But we are not Defenseless (1/3)

National Space Weather Program

The NSWP is a federal interagency initiative in the US established in 1995 to improve our capability to make timely and reliable predictions of significant disturbances in space weather and to provide this information in ways that are tailored to the specific needs of those who are potentially affected by them.

GOAL:

I. Discover and understand the physical conditions that produce space weather and its effects.

I.Develop and sustain necessary observational capabilities.

II.Provide tailored and accurate space weather information where and when it's needed.

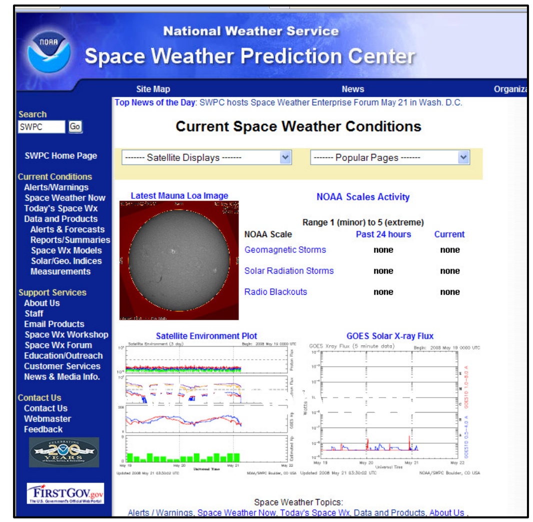
III.Raise national awareness of the impacts of space weather.

IV.Foster communication among government, commercial, and academic organizations.

www.ofcm.gov

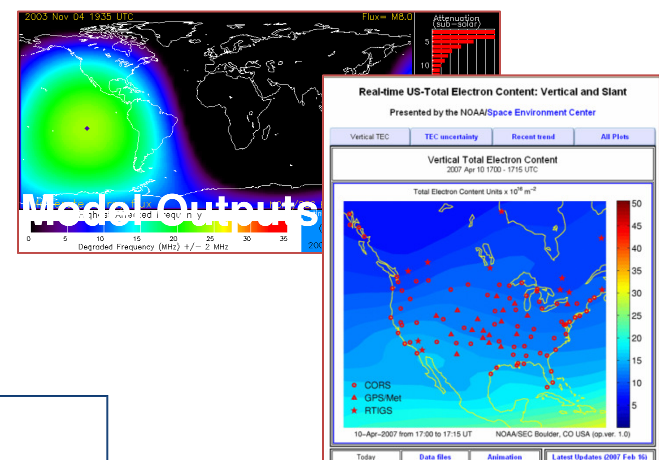
But we are not Defenseless (2/3)

NOAA SWPC



Space Weather Products and Services

- **Watches:** The conditions are favorable for occurrence
- **Warnings:** disturbances that are imminent, expected in the near future with high probability
- **Alerts:** observed conditions meeting or exceeding thresholds
- **Forecasts and other routine products**

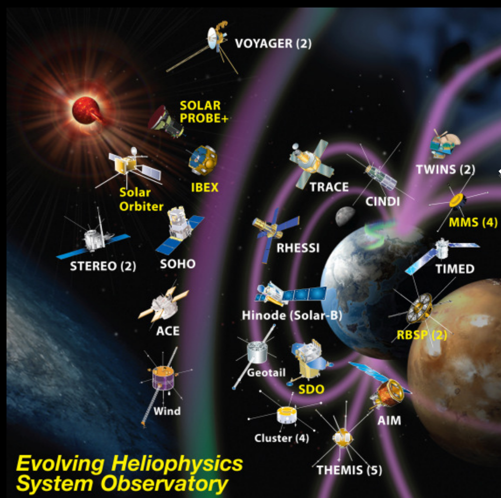


www.spaceweather.gov

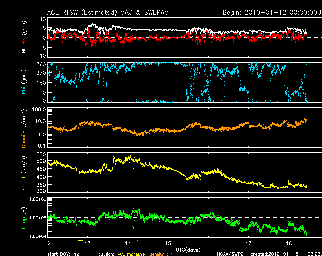
But we are not Defenseless (3/3)

NASA Heliospheric System Observatory (HSO): SWx Today

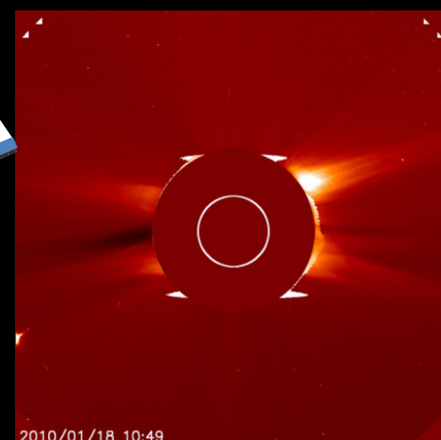
HSO



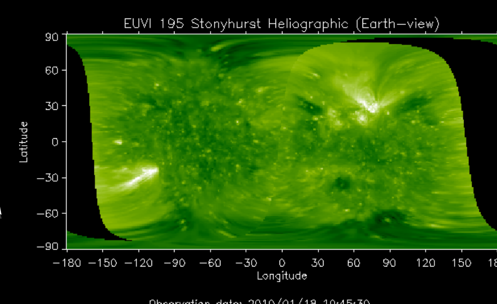
ACE



SOHO

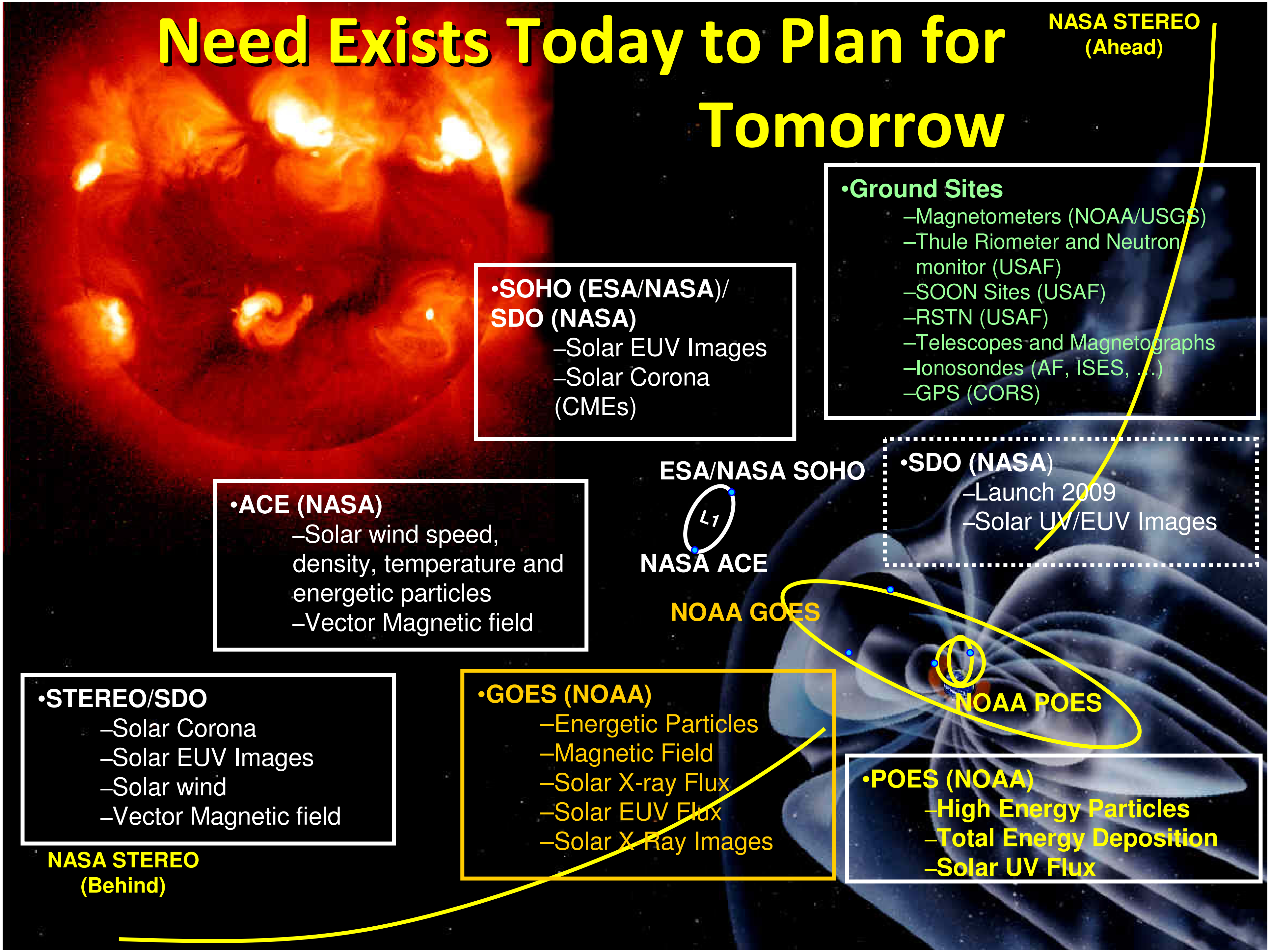


STEREO



CCMC data
Models+Theory

SWx Users



Need Exists Today to Plan for Tomorrow
NASA STEREO (Ahead)
•Ground Sites
–Magnetometers (NOAA/USGS)
–Thule Riometer and Neutron monitor (USAF)
–SOON Sites (USAF)
–RSTN (USAF)
–Telescopes and Magnetographs
–Ionosondes (AF, ISES, …)
–GPS (CORS)
•SOHO (ESA/NASA)/ SDO (NASA)
–Solar EUV Images
–Solar Corona (CMEs)
ESA/NASA SOHO
L1
NASA ACE
•SDO (NASA)
–Launch 2009
–Solar UV/EUV Images
•ACE (NASA)
–Solar wind speed, density, temperature and energetic particles
–Vector Magnetic field
NOAA GOES
NOAA POES
•STEREO/SDO
–Solar Corona
–Solar EUV Images
–Solar wind
–Vector Magnetic field
NASA STEREO (Behind)
•GOES (NOAA)
–Energetic Particles
–Magnetic Field
–Solar X-ray Flux
–Solar EUV Flux
–Solar X-Ray Images
•POES (NOAA)
–High Energy Particles
–Total Energy Deposition
–Solar UV Flux

Steps Ahead

- Continued basic and applied research on solar event
- A need for systems analysis of long term loss of power
  Is there a "tipping point" leading to disaster?
- Making sure observations are in place to provide the data we need for forecasting?
- Formal "risk analysis" of a major storm and its impact

More Study is Needed to Know How Likely is a Superstorm
(and how bad can it be?)

Assess the frequency of severe solar storms at regional levels

Describe the effects of increasingly severe storms on electrical power system

Examine the system impact of long term loss of power on other critical infrastructure

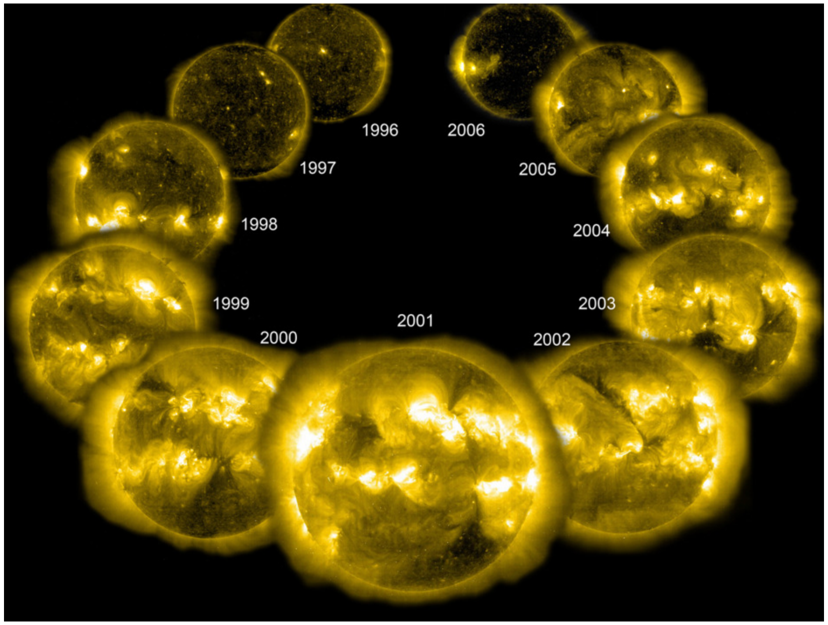
Is there a "tipping point" that leads to cascading impacts?

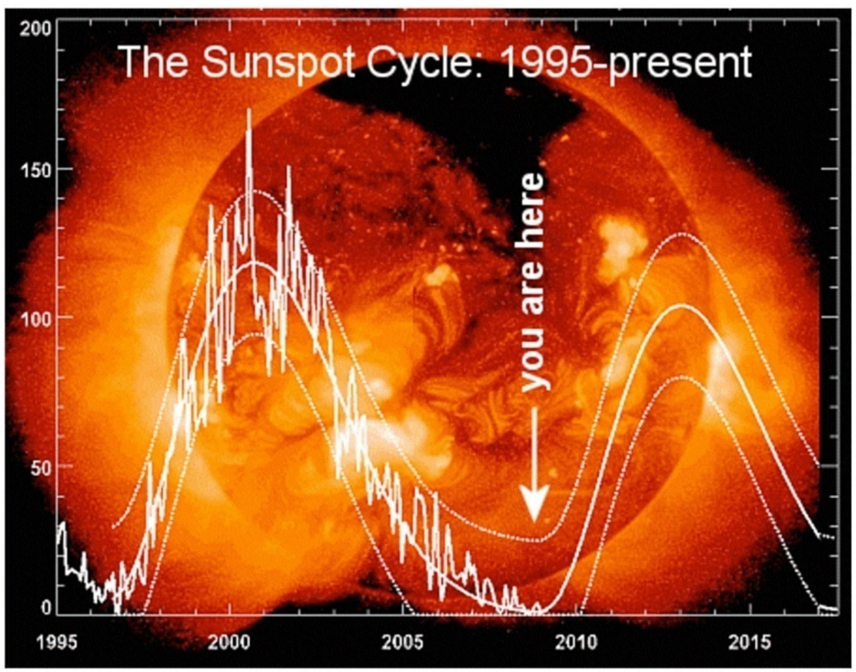
Final Remarks

The purpose of this briefing was to inform COPUOS about space weather and for you to look at potential exposure of your nation/business to SWx and plan accordingly, because it is not just the plot of a Hollywood movie, it is a real risk for today's business.

We are here today to lay the groundwork for an international effort to ensure that the observations and infrastructures are in place to provide effective operational warning in the future for the world.

Encountering an Extreme Solar Minimum





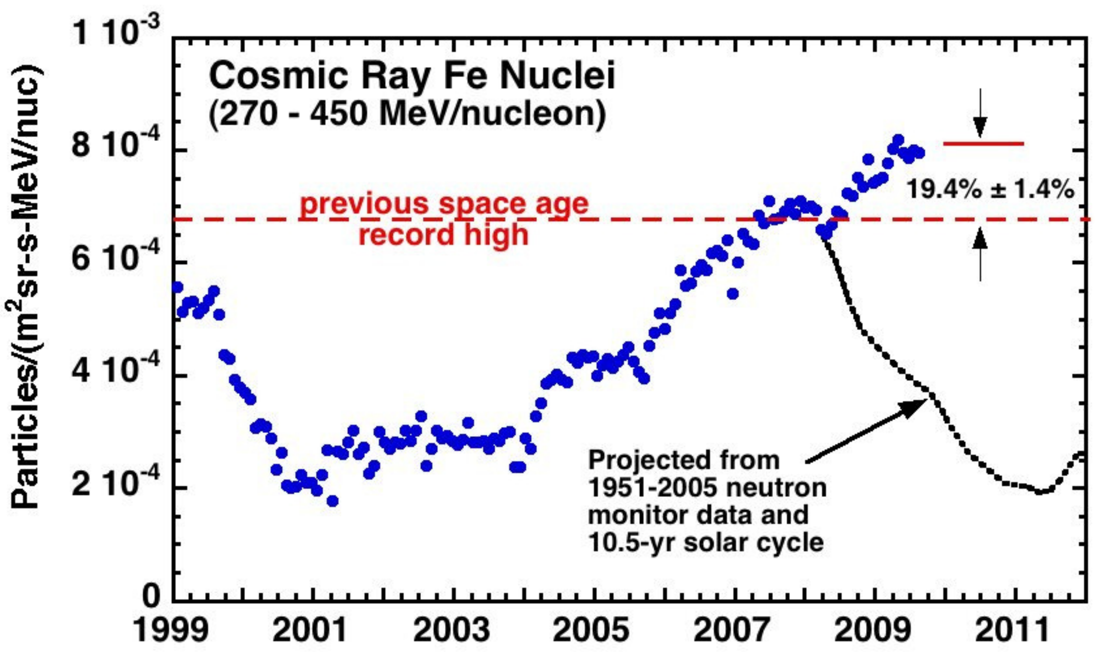
Since the dawn of the space age:

- Longest period with no sunspots
- Lowest solar X-ray flux
- Cosmic Rays Have Hit a Space Age High
- The Ionosphere Has Collapsed
- Space Junk Is Accumulating
- Radiation Belts are Charged with Killer Electrons
- A Drop in Solar Irradiance affects Earth Temperatures
- The Sun's Magnetic Field is in a Strange State

Cosmic Rays Hit A Space Age High

"In 2009, cosmic ray intensities have increased 19% beyond anything we've seen in the past 50 years," says Richard Mewaldt of Caltech. "This is a direct result of solar minimum and a weakened solar magnetic field."

Data from NASA's ACE spacecraft reveal the surge in biologically-significant iron nuclei:



"If current trends continue, the cosmic ray flux could soon be 30% or more higher than previous records," adds Mewaldt.

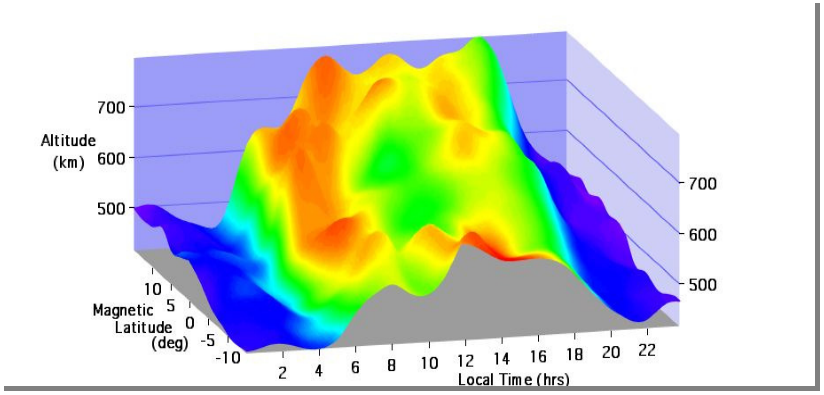
The Ionosphere Has Collapsed

Space Has Never Been Closer To Earth

Sensors onboard the US Air Force C/NOFS satellite have recorded a record collapse of the ionosphere. The nighttime ionosphere is only 260 miles above Earth's surface, a sharp decrease from the usual value of ~400 miles. The ionosphere is also 100 degrees cooler than expected.

Solar minimum is to blame. Extreme UV radiation, which heats and ionizes the upper atmosphere, has dropped 6% compared to previous solar minima.

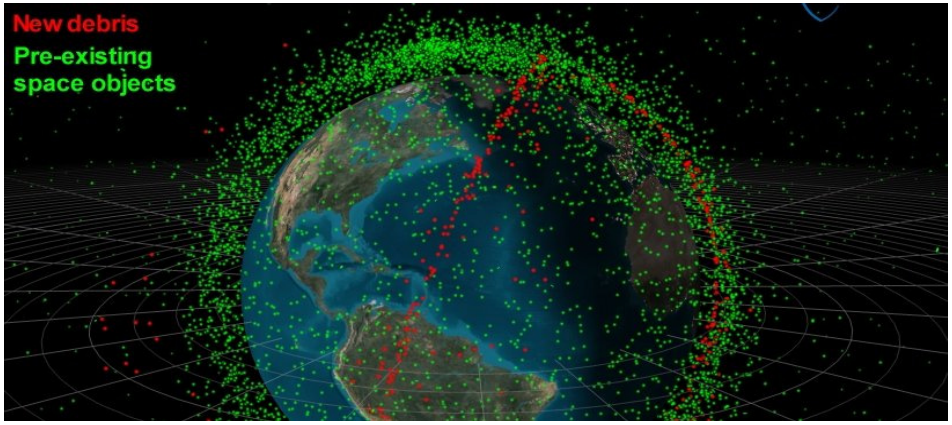
This dramatic change affects terrestrial radio communications, curtailing over-the-horizon shortwave reception and causing unusual forms of scintillation in GPS signals.



CINDI) sensors onboard C/NOFS made the first map of the top of Earth's ionosphere. The top of Earth's ionosphere expands and contracts from day to night, but was much closer to Earth than researchers expected.

Space Junk is Accumulating

In February 2009, the Kosmos 2251 and Iridium 33 satellites collided over northern Siberia, spewing thousands of fragments into low-Earth orbit. The usual decay of these fragments has been slowed and almost stopped by the effects of extreme solar minimum.



The collapse of Earth's upper atmosphere reduces aerodynamic drag on satellites and space junk.

If Solar Cycle 24 is of average strength, 50% to 75% of Kosmos/Iridium debris will decay within the next 11 years.

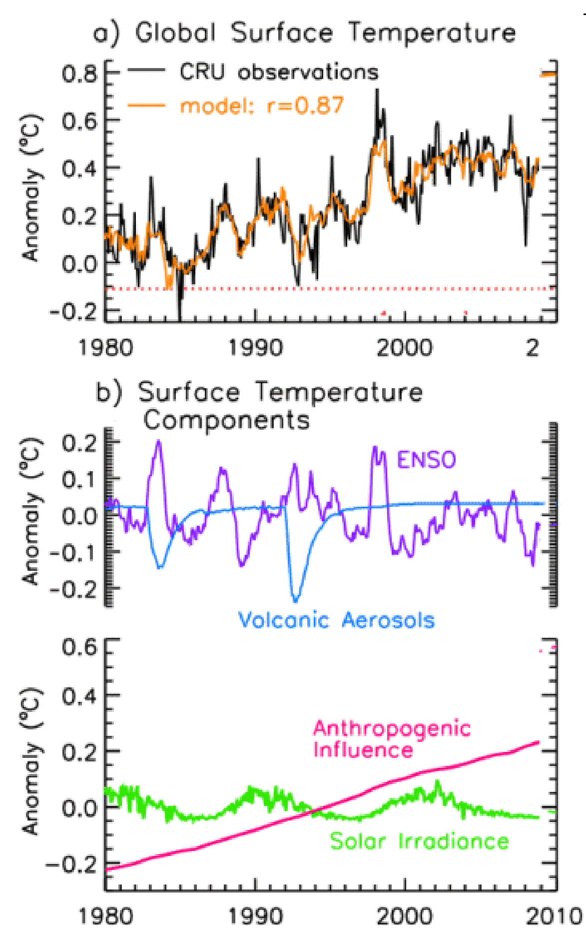
On the other hand, if solar minimum continues or if Solar Cycle 24 is very weak, as much as 80% of the debris will remain in orbit.

This is according to simulations done by the Orbital Debris Group at JSC.

Solar Minimum vs. Greenhouse Gases

Solar minimum is not a permanent solution to global warming, but it can provide some temporary relief, according to a study by Judith Lean (NRL) and David Rind (GISS), who modeled the effects of volcanoes, greenhouse gases, ENSO, and solar irradiance on climate.

"A 0.1% decrease in the Sun's irradiance has counteracted some of the warming action of greenhouse gases from 2002 - 2008," says Lean. "This is the reason for the well-known 'flat' temperature trend of recent years."



Reference: Lean, J. L., and D. H. Rind (2009), How will Earth's surface temperature change in future decades?, *Geophys. Res. Lett., 36*, L15708