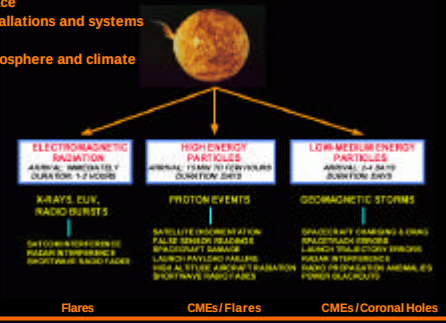
Space Weather Effects

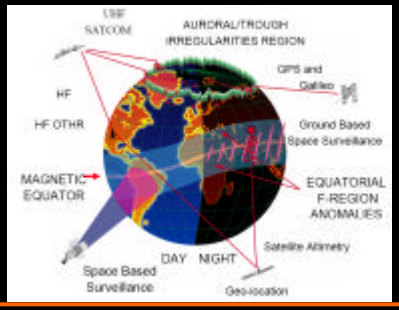
Effects from Solar Storms

- **Effects on Space based infrastructure**
- **Effects on communication with space systems**
- **Effects on humans in space**
- **Effects on terrestrial installations and systems**
- **Effects on terrestrial atmosphere and climate**



Satellite Communications

Satellite communication is normally thought of as a robust means of communication, not sensitive to environmental impacts. This perception is not totally accurate. Satellite communication can be and is affected by the environment in which it operates



Satellite Communications

Space environmental effects on satellite communication can be separated as to

(1) effects on the space segment (ie the satellites – depends on the orbit),
(2) effects on the ground segment (ie the Earth station), and
(3) effects on the signals propagating through the Earth's lower and upper atmosphere.

Satellite Failures due to Space Weather Effects

- Anomalies due to spacecraft surface and internal charging (Marecs, ECS, Meteosat, TELE-X,.....)
- Latch-up induced failures (ESR-1, PRARE, Equator-S,.....)
- SEU's in linear circuits...(Anik 1 &2)
- Solar Array problems/degradation (Tempo, PanAm, ECS,....)

More recent satellite failures:

- Telestar 401 (Jan 11 1997)
  - TV links etc..
- Galaxy IV (1998)
  - silenced 80% of pagers in North America

More than 12 satellites lost due to Space Weather Effects

Last 6 years space losses may have exceeded $500 million

Commercial interests often do not allow anomaly reporting.

Satellite Failures – Galaxy IV

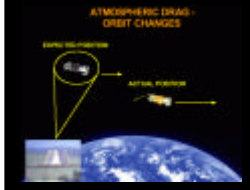
- Galaxy IV is a $250 million satellite was owned by PanAmSat and parked in a geostationary orbit 35.000 km above the Earth.
- The satellite was transmitting pagers, internet (PC Direct), television feeds and wire service news transmission.
- On 19 May 1998 the Galaxy IV satellite spun out of control.
  - Over 80% of all pagers in USA were disrupted (40 million pagers).
    - Doctors, nurses, detectives, and even drug dealers were discovering that they had been out of touch all night.
  - Direct PC Internet
  - CBS's radio and television feeds, NPR, the Chinese Television Network, CNN's Airport Network, Reuters text-based news service.
  - Weather information to airports (many airlines such as American, UA, USAir, Fedex) lost some of their weather tracking information.
  - Credit card machines at gas pumps and hampered ticket sales for the Texas lottery

Satellite Failures

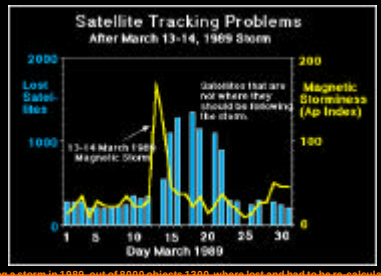
Was this failure caused by the Sun or just "random" ?

- In the same period, while the Sun was very active and the space environment was very hostile, other satellites also had problems:
  - Germany's Equator-S failed
  - Several others suffered blackouts or operational problems (NASA's Polar and Japan's GMS satellites)
  - Motorola apparently lost 4 of the Iridium satellites in that quarter of 1998 before the where even put online.
- Whether or not this incident was caused by space weather, it certainly shows the vulnerability of our society to individual spacecraft loss.
- The vast number of users affected by the loss of just one satellite shows how dependent society is on space technology and how fragile communications systems can be.
- In the days, and weeks after the Galaxy VI failure, PanAmSat moved the dead satellite to a higher orbit and moved Galaxy VI to Galaxy IV's position. Within days, most of PanAmSat's customers were back online.
- The satellite was insured fro $165 million. Still PanAmSat lost tens of millions in business and hardware costs.

Orbit tracking of Satellites



Increased satellite drag and loss of orbit tracking magnifies the risk of collisions with orbiting debris



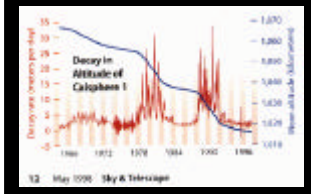
During a storm in 1989, out of 8000 objects 1300 where lost and had to here calculated ...

Increased Drag on Satellites

The expanding atmosphere causes an increased drag on low orbit satellites. In addition to loose altitude they can also start tumbling since the satelli tes in most cases are non-symmetrical

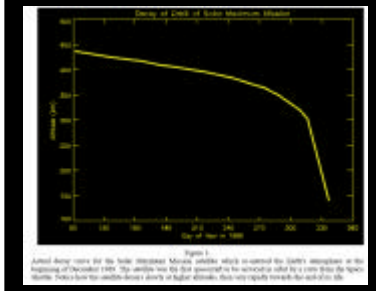
Vary with the solar cycle.

- Skylab re-entered several years earlier than planned



SMM – Solar Maximum Mission

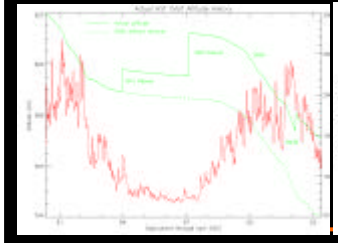
- XMM dropped 5 km during the March 89 storm
- SMM reentered the Earth's atmosphere and burned-up on December 2, 1989.

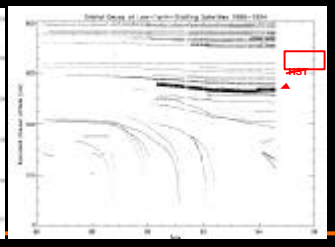


HST Orbit History

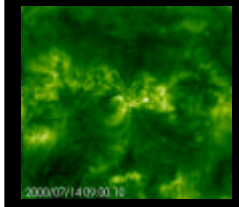
The Hubble Space Telescope drops 10-15 km per year

- Re-boosted by the Shuttle

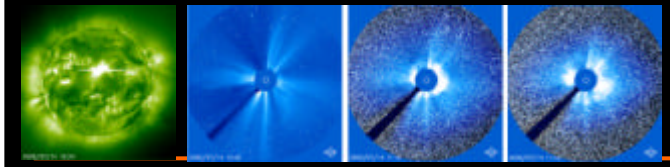




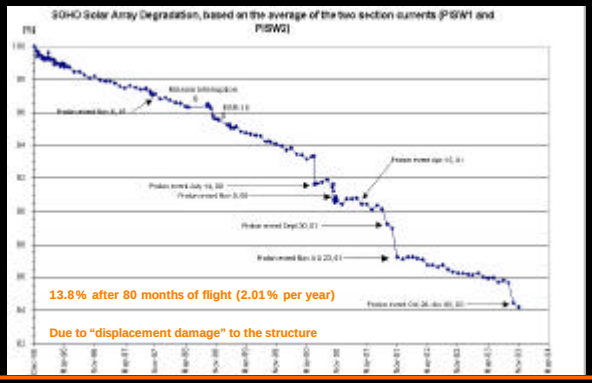
Solar cell degradation



- Some spacecraft have had the efficiency of their solar cells reduced by over 30% in a single large solar particle event. This effectively reduces the lifetime of the spacecraft by several years



Solar Array Degradation

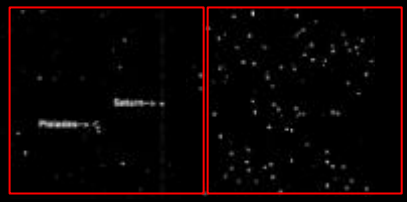


13.8% after 80 months of flight (2.01% per year)

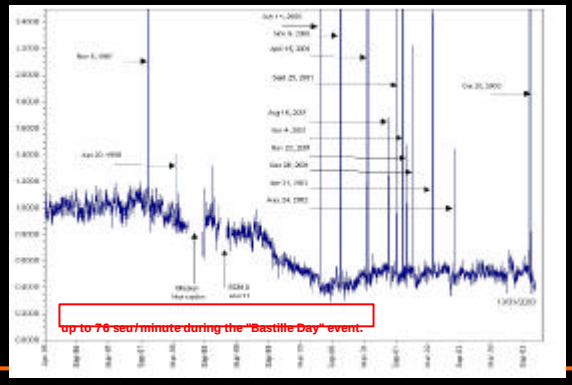
Due to "displacement damage" to the structure

Star Sensor Units "Blinded"

- When particles hit the CCD they generate electrons which charge up the pixels just like the regular photons, producing images similar to a star.
- Confuses the attitude control unit and can lead to tumbling.

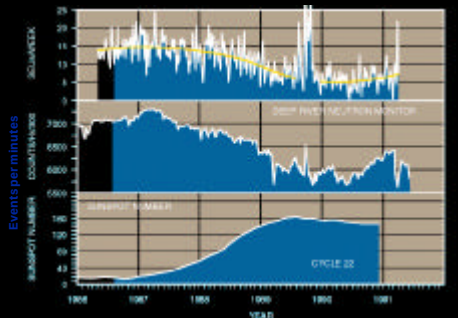


Solid State Recorder Single Event Upsets

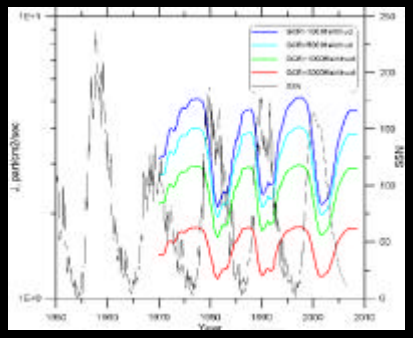


up to 76 seu/minute during the "Bastille Day" event.

Solid State Recorder Single Event Upsets



Cosmic Radiation Measured on the MIR station



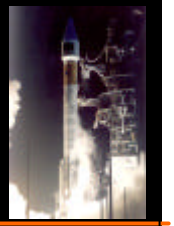
IBM ThinkPad on MIR experience upsets every 9 hour. On the Space Shuttle sometimes 1 per hour.

Launch Errors due to Density Variations

Excessively high or low geomagnetic conditions can produce atmospheric density variations along a proposed launch trajectory

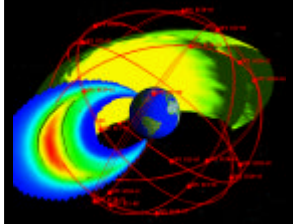
- **Density variations could fall outside the launch vehicle's capacity to compensate**
- **The density profile with altitude will determine how early the protective shielding around a payload can be jettisoned.**

In the past, payloads have also been damaged by attempted deployment during geomagnetic storms or proton events

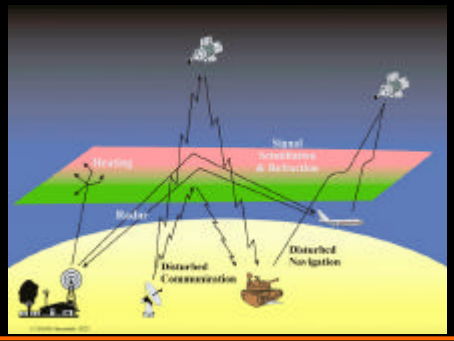


Navigation systems (GPS)

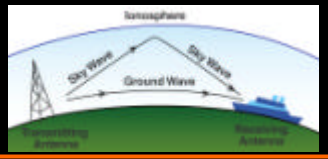
- **When the ionosphere between the satellites and the user becomes turbulent and irregular, the signal may "scintillate" and prove difficult to track**
  - loss of signal lock on one or several satellites
  - Both single and dual frequency systems may be affected
- **The Total Electron Content (TEC) along the path of a GPS signal can introduce a positioning error (up to 100 m)**
- **The effects on GPS could be one of the most significant space weather effects due to the planned reliance of this system in the future.**

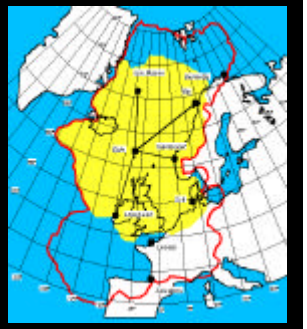


Effects on Military Systems



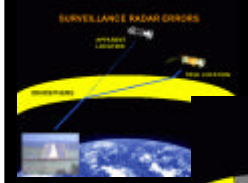
Navigation LORAN C





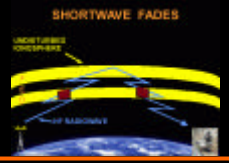
A 7-10 km height change of the lower ionosphere can give position errors of 1-12 km

Effects on Military Systems



- Some military early-warning systems are affected. Errors in tracking missiles makes it hard to intercept a hostile missile.
- Over-the-horizon radar bounces signals off the ionosphere in order to monitor the launch of aircrafts or missiles.

- HF Satellite communication will be out for half an hour to several hours due to a large flare
  - e.g. disrupt fire support requested via HF
  - this posed a real problem during the Persian Gulf war



The Space environment could play a significant role in deciding the outcome of future battles by influencing the way the customers control and apply weapon control.

Effects on Military Systems

- Some laser guided bombs use GPS to navigate

Effects on Civil Aviation

- Aircrew radiation exposure
- Effects on aircraft avionics, communications and GPS navigations systems

Recent effects on polar routes

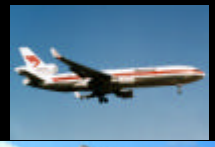
United Airlines: Reported several cases were flights had to be re-routed to less optimal routes due to loss of communication or radiation storms.

One example was a storm that caused a flight to be diverted from a polar rout, requiring additional fuel at Tokyo and extended the flight with 5 hrs 30 min.

During another period (March 30 – April 21, 2001) 25 flights were flown on less than optimal polar routes due to HF communication problems.

Northwest Airlines: diverted a Detroit-Beijing flight to a non-polar route due to both HF communication problems (radio blackout) and a solar radiation storm, forcing an unscheduled stop at Fairbanks for fuel. This caused a 3 hour delay and an estimated $100,000 cost to NWA.

Continental Airlines: Diverted their daily flight from Newark to Hong Kong for the second day in succession based on a S3 level of solar radiation storm effects and their HF operation.



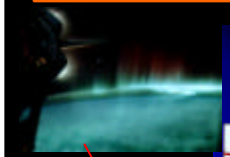
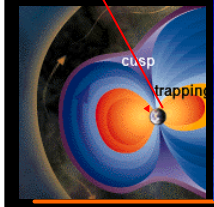
Re-routing and delays are costly to the airlines:
fuel cost? crew delays? additional crews

High Energy Particles Hazards to Humans

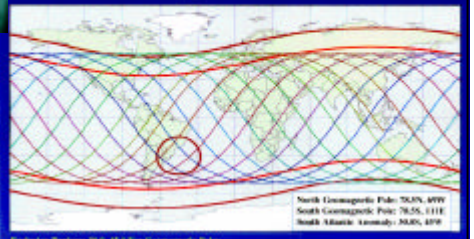


- **Humans in space**
  - Space Shuttle, International Space Station, missions to Moon and Mars
- **Crew / Passengers in high-flying jets and polar routes**
  - Concorde carried radiation detectors
  - Passengers may receive radiation doses equivalent to several chest X rays.

ISS and Shuttle – fairly well protected

Space Station Orbit Is Exposed to High Energy Solar Particles

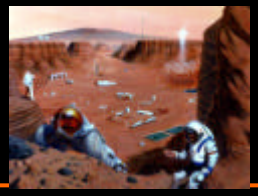


Future space flights – Moon and Mars

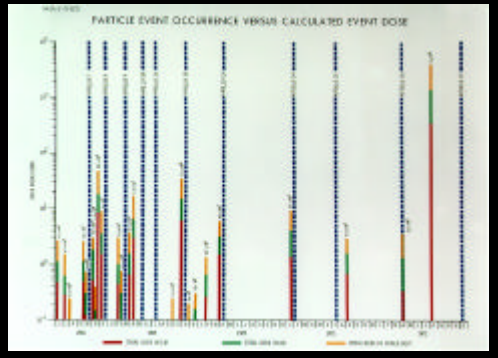
Will humans survive a mission to Mars?

- **During the last 45 years humans have only been in deep space for a few days at a time (Apollo missions to the moon).**
- **Outside our protective magnetosphere humans will receive a lot more radiation and over a much longer time that was the case during the Lunar missions.**

- **Protection during flight AND at the surface on Mars will be a big challenge.**

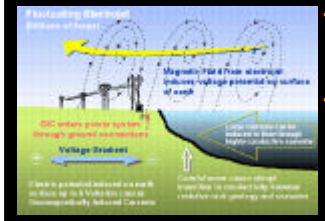


Proton events and Apollo Lunar landings



1972 event: 4000 REM in space suit, 1000 REM in Lunar Module

Geomagnetic Induced Currents



- **These currents will leak into all long conductors:**
  - power grids,
  - oil and gas pipelines (increased corrosion)
- **Train light signals can be affected (two documented events in Sweden)**

Damage to Transformers

Damage to a transformer at a power plant Delaware, New Jersey i march 1989.

Price: 10 mill USD

Repair can take up to 1 year.

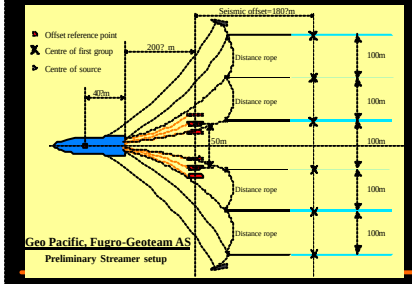
In this particular case they were lucky to find a used one from a shut down plant. Took only 6 weeks to restore

Sweden: simultaneous power loss in six 130 kV power distribution lines

Chicago: Five transformers in the Chicago area failed due to elevated geomagnetic activity in April 94

Geological Surveys

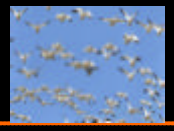
Magnetic storms affect surveys for minerals which use either ground-based or airborne magnetometers to measure the small changes in the earth's magnetic field associated with deposits of minerals. These surveys are more difficult, perhaps impossible, during major magnetic storms.



- **Directional drilling is hampered**
  - Oil industry relies on geomagnetic maps to guide the drill and monitor the well direction.

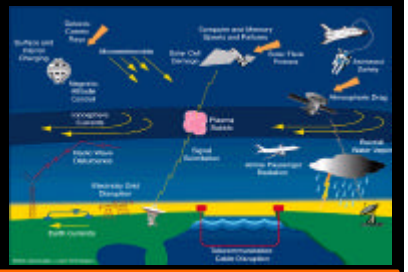
Sensitive magnetic sensors - Geological Surveys

- **The navigational abilities of homing pigeons are affected by geomagnetic storms**
- **Pigeons and other migratory animals, such as dolphins and whales, have internal biological compasses composed of the mineral magnetite wrapped in bundles of nerve cells.**
- **Although this is probably not a pigeon's primary method of navigation, researchers believe that this biological compass is affected by geomagnetic storms.**
- **"smashes" is a term used during homing pigeon releases when only a small percentage return home.**
- **Pigeon handlers have learned to ask for geomagnetic alerts and warnings to aid in the scheduling of races.**



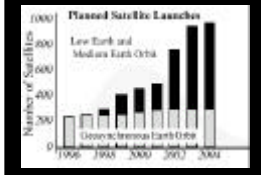
Space Weather: Why should we care?

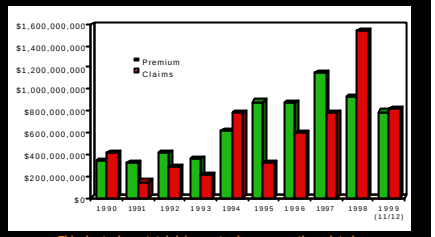
- **We are more and more dependent upon the advanced technological systems that orbit our planet**
- **The most rapidly growing sector of the communication market is satellite based**
  - Broadcast TV/Radio,
  - Long-distance telephone service, Cell phones, Pagers
  - Internet, finance transactions
  - 250 million users if GPS
- **Change in technology**
  - more sensitive payloads
  - high performance components
  - lightweight and low cost
- **Humans in Space**
  - More and longer manned missions



Assets in Space - Satellite Insurance

- **Total value of more than 600 satellites currently in orbit is about $50-100 billion**
  - 235 of these are insured (value: $20 billion)
- **Growing market: 900 commersial satellites are expected to be launched the next 10 years**
  - potential insured value $80 billion

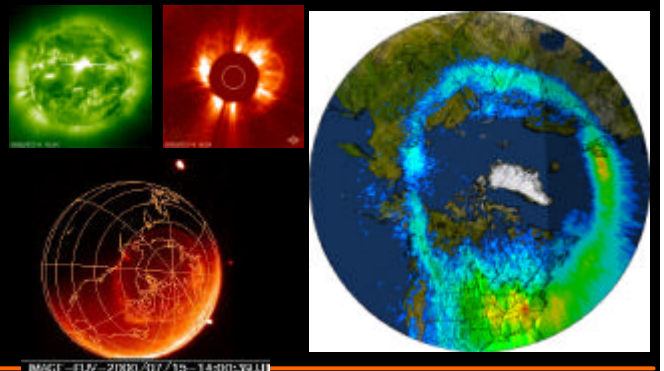




This charts shows total claims, not only space weather related
Estimated $500 million in damages due to space weather last 4 years

Source: USAU

The 14 July 2000 Event



Reported effects from the 14 July Storm
Effects on Satellites

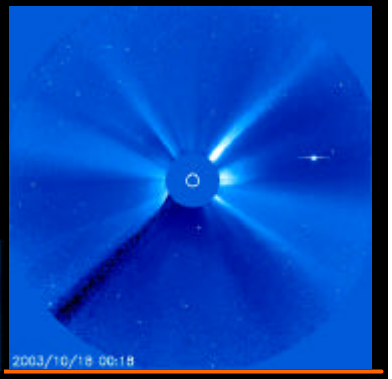
- ASCA – Japanese spacecraft lost, spinning out of control due to increased "drag" which disturbed the angular momentum
- ACE temporarily "lost" output from its solar wind velocity measuring sensor due to the high flux of energetic particles
- All the solar monitoring satellites: SOHO, YOHKOH, and TRACE .had their optics essentially obscured by the arrival of the high energy ions.
  - **SOHO spacecraft suffered permanent solar panel output degradation (estimated to be the equivalent of 1 year of normal degradation).**
  - **Several of the SOHO instruments was turned off for safety reasons**
- WIND - Solid State Power Amplifier 1 (SSPA#1) experienced a power loss of 25% (29 to 22 W)
  - **The degraded output (22 W) a less optimal science orbit after the next planned orbit adjustment (elliptic orbit reduced from 255 to 220 Earth radii)**
  - **No science data for 2 days**
- OERSTEDT - went "dead" but was recovered a few days later
- Several space crafts experiences attitude problems because of star tracker problems
  - **e.g. CHAMP which was launched during the event**
- A number (names and counts not specified due to commercial or government sources) of GEO communication satellites lost pointing control and had to be manually oriented from ground commands. (Source is Eamonn Dailey, ESTEC)
  - **A commercial geo-synchronous spacecraft lost a transponder due to SPE.**
- There were hours during which the magnetopause was Earthward of the GEO orbit around the Sun-Earth line and a sector on each side of that line.
- QuikSCAT – Both 1553 buses went down
- NEAR: The solar proton event caused the X-ray/Gamma-ray Spectrometer (XGS) on NEAR to shut down for two days.
- Both GOES-8 and -10 "lost" the output from their > 2 MeV electron sensors.
- AKEBONO (Japanese research sat.): disabled the spacecraft computer operation

When the Sun went Crazy

Active regions 10484 & 10486 produced, together:

11 X-Class Flares
36 + M-Class Flares
Countless C-Class

At least **15** "halo" CMEs
Many other small CMEs and jets.

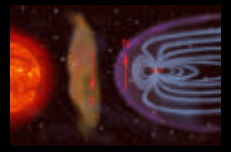


Effects from the Halloween Storms

Stirling, Scotland

Luceville, Quebec

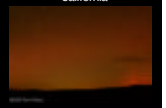
Stockholm, Sweden



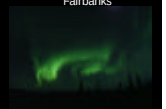
- More than 20 satellites and spacecrafts were affected (not including classified military instruments), 1 Japanese satellite lost
- Severe HF Radio blackout – affected commercial airlines
- FAA issued a first-ever alert of excessive radiation exposure for air travellers
- Power failure in Sweden
- Climbers in Himalaya experienced problems with satellite phones.
- US Coast Guard to temporarily shut down LORAN navigation system.

Anchorage

California

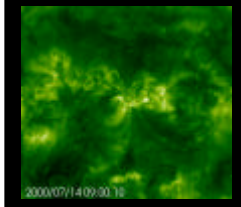


Fairbanks



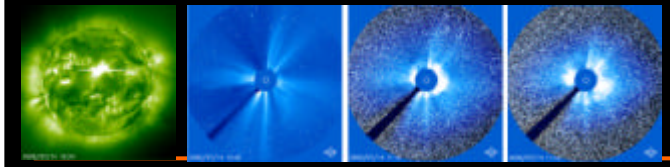
Effects on the Earths atmosphere Climate change

Solar Storms Takes Toll on Ozone

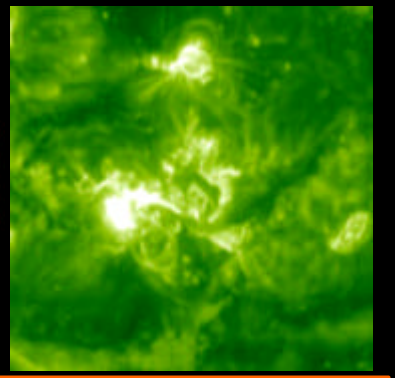


- Large proton events deplete the upper level ozone for weeks to month (Jackman et al. GRL 28, 2883, 2001).
- These short term effects can destroy up to 70% of the ozone in the middle mesosphere.

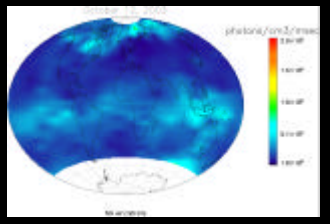
Solar storm and proton event on 14 July 2000 (SOHO images)

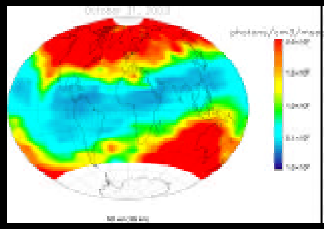


Big Sunspots and a Flare



Oct – Nov, 2003 solar storm shows large effect on NO emission at 125 km





SABER Nitrous Oxide measurements before storm

October 12, 2003

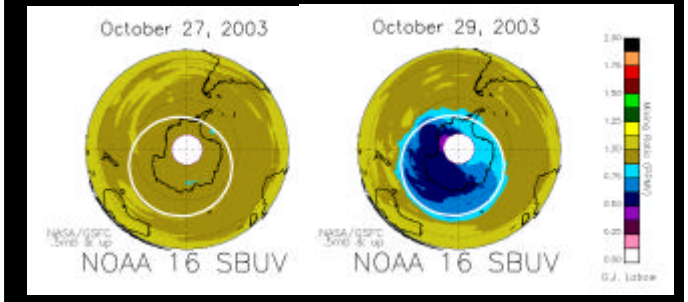
Nitrous Oxide at storm peak

October 31, 2003

Courtesy of
J. M. Russell III, M. G. Mlynczak
and the SABER Science Team

SPE affects Ozone in the Southern Polar Cap

(at 0.5 hPa or ~55 km)



Source: Charles Jackman & Gordon Labow (NASA)

TRMM observes an ocean reflection of the solar flare!

The extremely intense radiation coming from the flare saturated X-ray detectors for 11 minutes. The burst of solar microwaves, traveling from the sun to the Earth in 8 minutes, reflected off the ocean surface. The radiation was so intense that it saturated the 11-GHz TMI channels.