Space Weather Overview

What is “space weather” and what does it mean for aviation?

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University of Otago

Dunedin

NEW ZEALAND

3rd New Zealand Aviation Meteorology Symposium

Civil Aviation Authority of New Zealand, Wellington

9:40am Thursday 19 September 2019

What is Space Weather?

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NEW ZEALAND

Technology

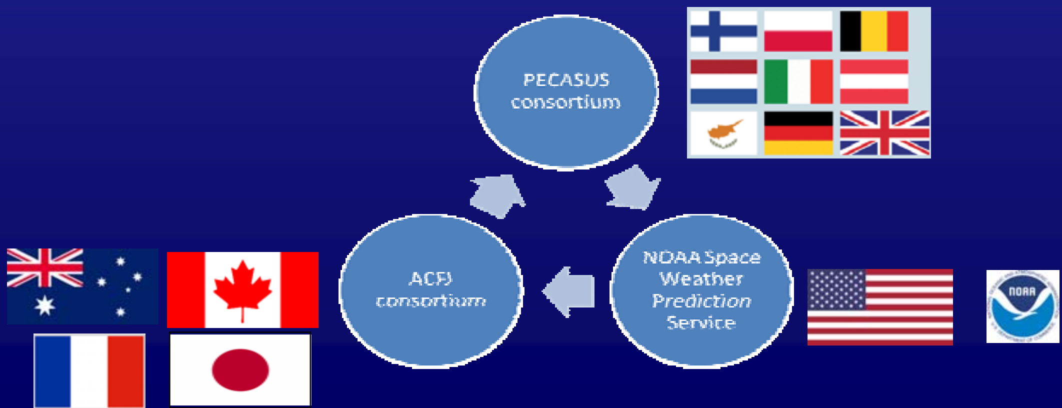
Impact

SpaceWx disruptions - ICAO

The International Civil Aviation Organization (ICAO) is the UN organisation to foster safe and orderly air travel.

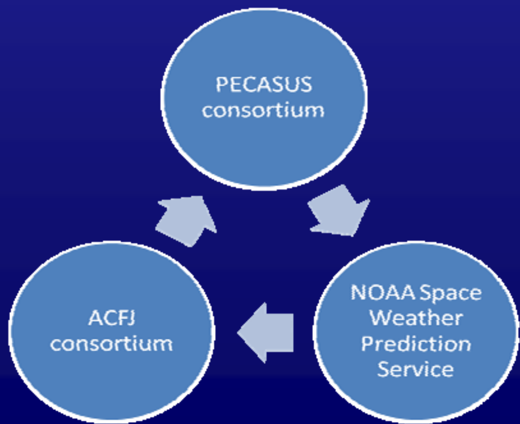
ICAO has identified solar flares and solar storms as potential hazards that affect communications, navigation, aircraft crew and passengers. They have requested early warnings of space weather activity.

Working with the WMO, global space weather forecasts are to be provided to the aviation industry **from late 2019 (7 Nov)**.



Process for new services for aviation

- **2011** IATA (International Air Transport Association) requested ICAO for space weather services for civil aviation
- **2014** ICAO decided to develop space weather service centres (SWXCs)
- **2017** ICAO asked its member states about their interests to provide SWX
  - 8 states and 1 consortium (PECASUS) expressed their willingness to be audited
  - February 2018 Audit of all candidates
- **June 2018:** ICAO Council approved a new version of Annex 3 with specification of SWX services
- **October 2018:** Air Navigation Commission (ANC) made final recommendation of 3 global and 2 regional SWX centres:
  - Global: **PECASUS**, **USA,** and **ACFJ** (consortium of Australia, Canada, France, Japan)
  - Regional: China/Russia & South Africa
- **November 2018:** ICAO Council designated three global and two regional centres
- **December 2018 onwards:** Ad-hoc coordination group under the ICAO MET Panel MISD to develop coordination of SWX provision
- **7 November 2019:** **Start of operational Space Weather Advisory dissemination from three global centres**



ICAO Documentation

- State letter dated 9 June 2017 with its Annex
- Annex 3 to the Convention of ICAO (Standards And Recommended Practises - July 2018)
- Space Weather Manual (Doc 10100 - first edition 2018)

International Civil Aviation Organization | Organisation de l'aviation civile internationale | Organización de Aviación Civil Internacional | Международная организация гражданской авиации | منظمة الطيران المدني الدولي | 国际民用航空组织

Tel.: +1 514-954-8219 ext. 6717

Ref.: AN 10/1-IND/17/11 9 June 2017

Subject: Request for interest in providing a space weather information service

ICAO

International Standards and Recommended Practices

Annex 3 to the Convention on International Civil Aviation

Meteorological Service for International Air Navigation

Part I — Core SARPs

b. Ability to access observations (own observations and received from other space weather providers) of:

i. Coronal mass ejections and high-speed streams

ii. Geomagnetic storms

iii. Solar radiation storms

iv. Solar flares

v. Solar radio bursts

vi. Ionospheric activity

Manual on Space Weather Information in Support of International Air Navigation

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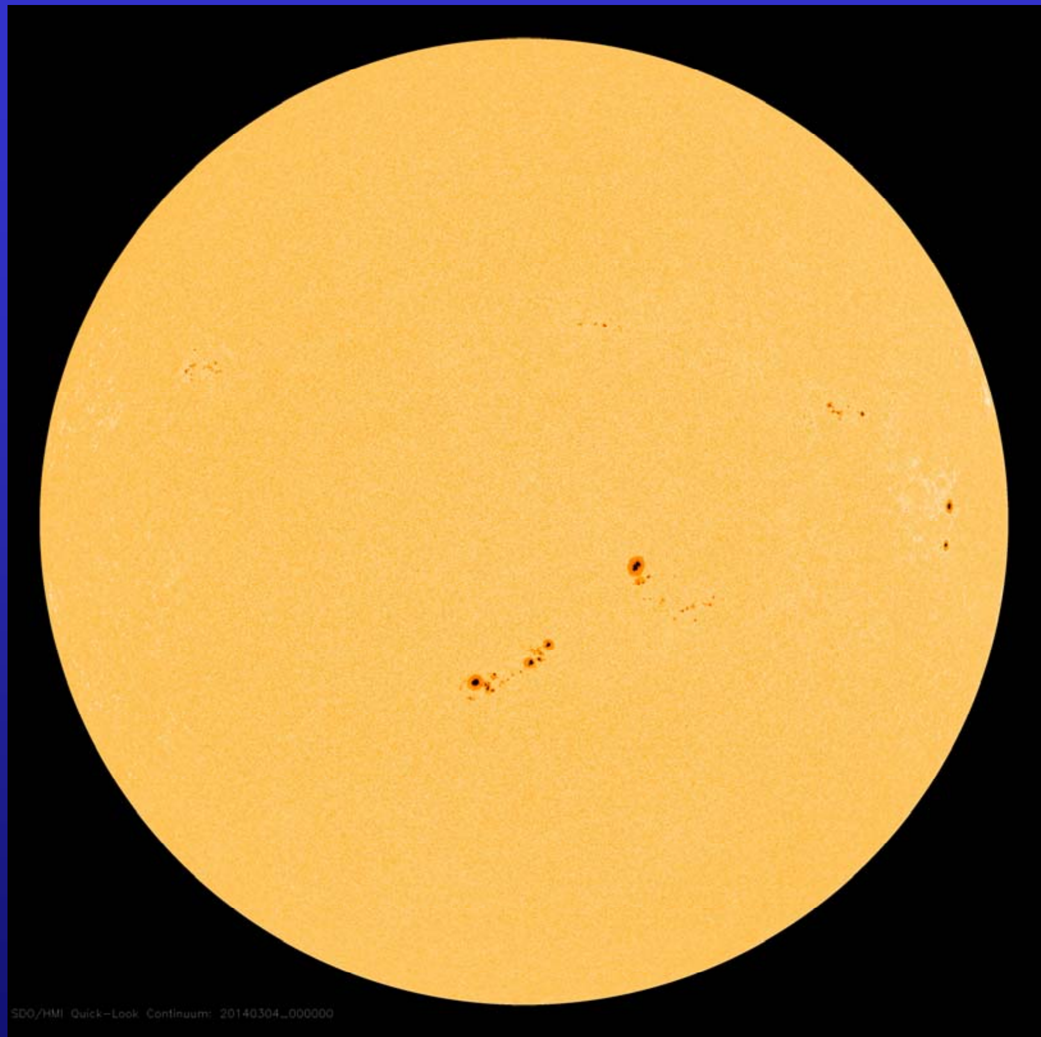
The Source of Space Weather



We normally view the Sun as being unchanging with a constant output. And as far as Sun light, warming the surface of the Earth, this is very close to be accurate.

Solar

Forcing

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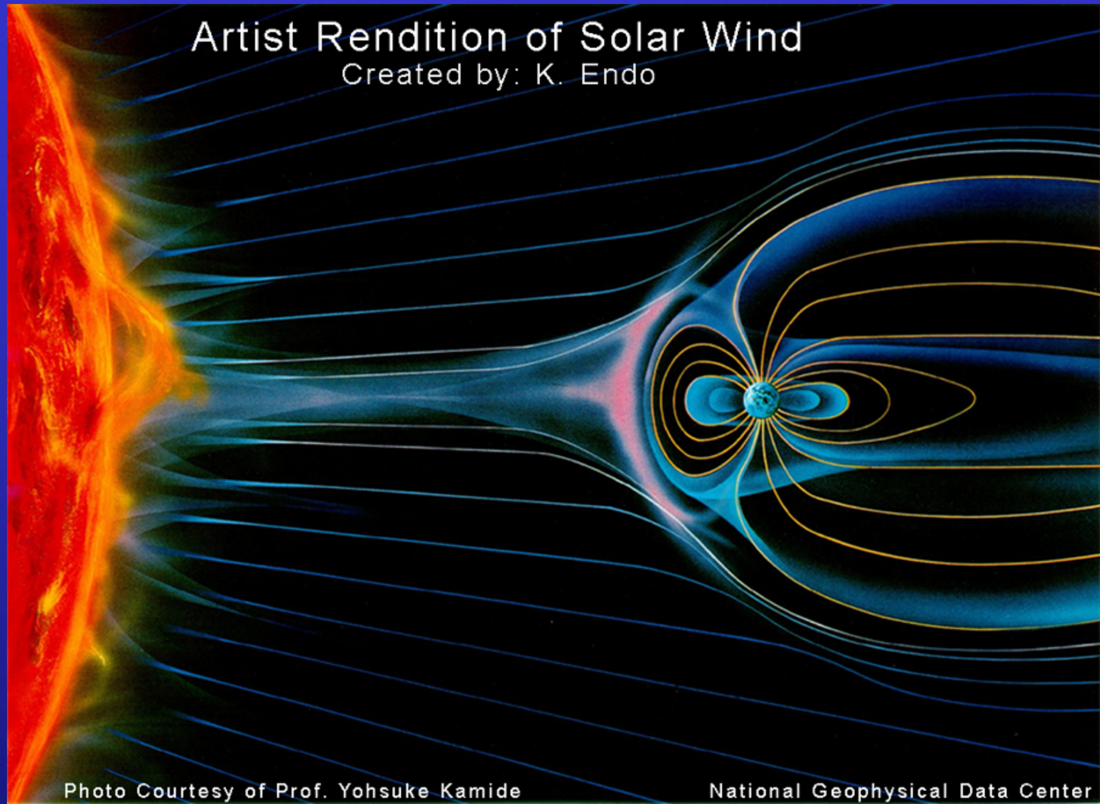
Sun-Earth connections



Solar

Forcing

The Sun "forces" the Earth-system in multiple ways. Gravitationally (e.g., tides), electromagnetic radiation (e.g., heat) but also through a near constant stream of particles we call the “solar wind”.

This is the normal situation, when the Sun is quiet.

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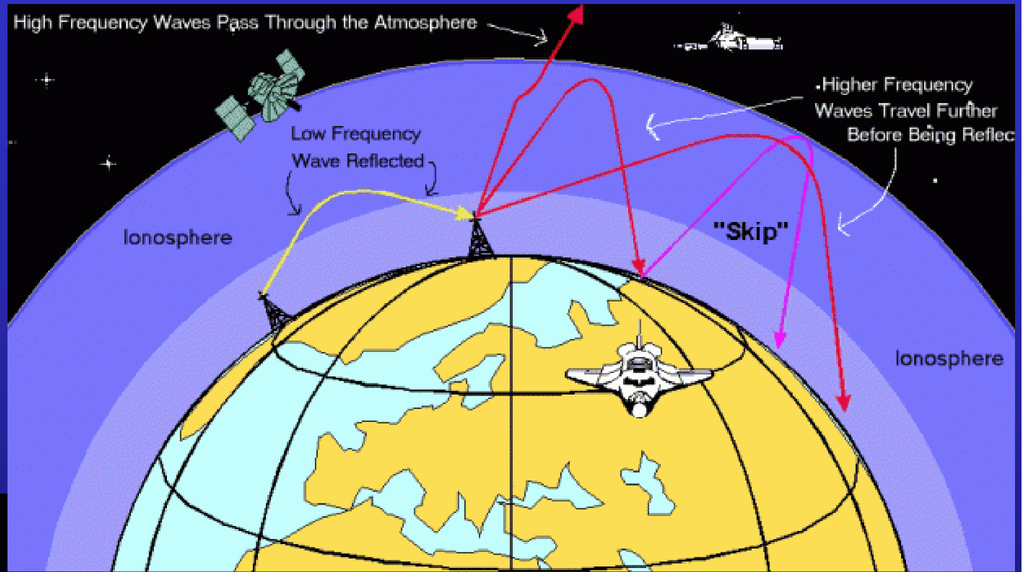
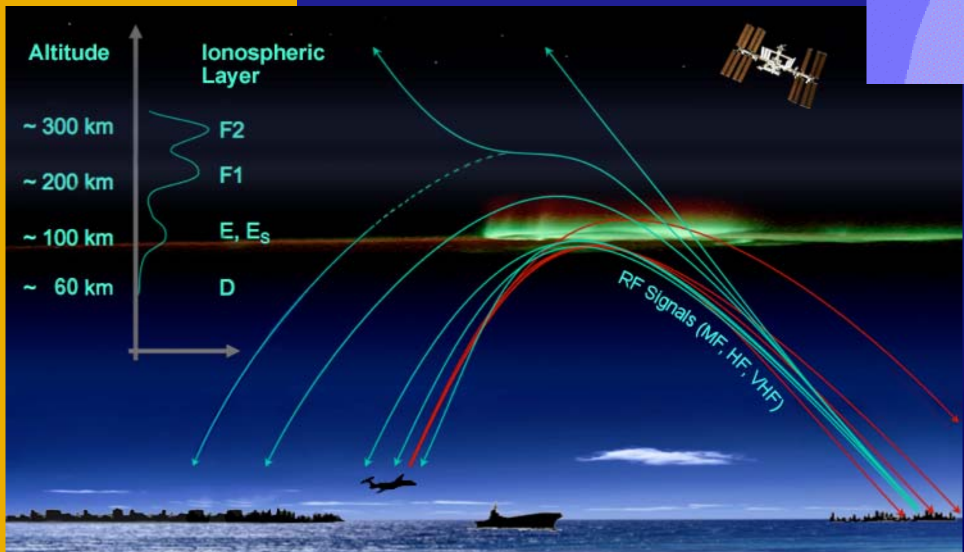
Sun-Earth connections: the ionosphere

Charged part of the upper atmosphere. A vital part of our technological framework.





Radio waves bounce off the ionosphere (long distance communications) or pass through the ionosphere to satellites (GPS, communication, etc).

Solar

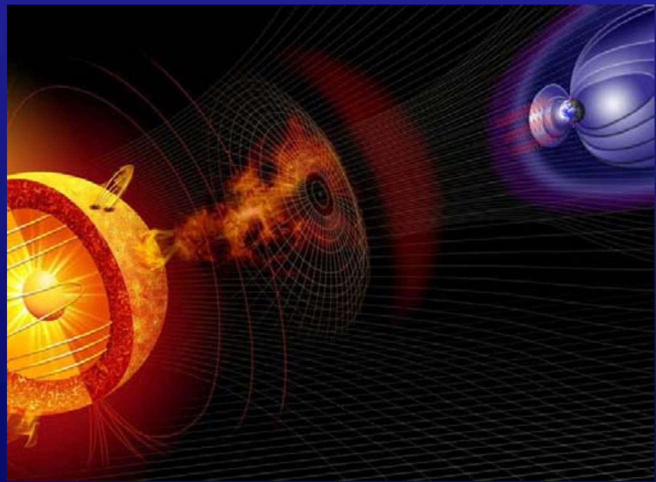
Forcing

What happens when the Sun goes bang?

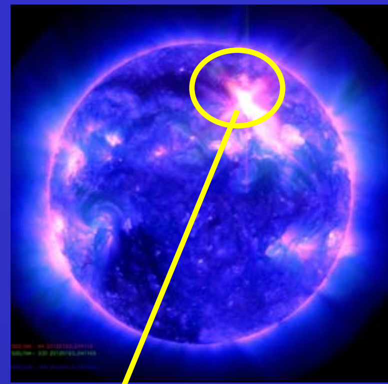
When the Sun is active, as well as the background total energy output of the Sun going up (a small amount), it is also more likely to "go bang" – that is, the biggest explosions in the solar system occur on the surface of the Sun. A number of processes can then happen, all of which have effects on the Earth's environment – and can impact human activity and technology.

A solar explosion can produce a number of different changes:

- X-ray flare
- Solar Proton Event/
  Solar Energetic Particle Event
- Coronal Mass Ejection
- Geomagnetic Storms



Solar X-ray Flares



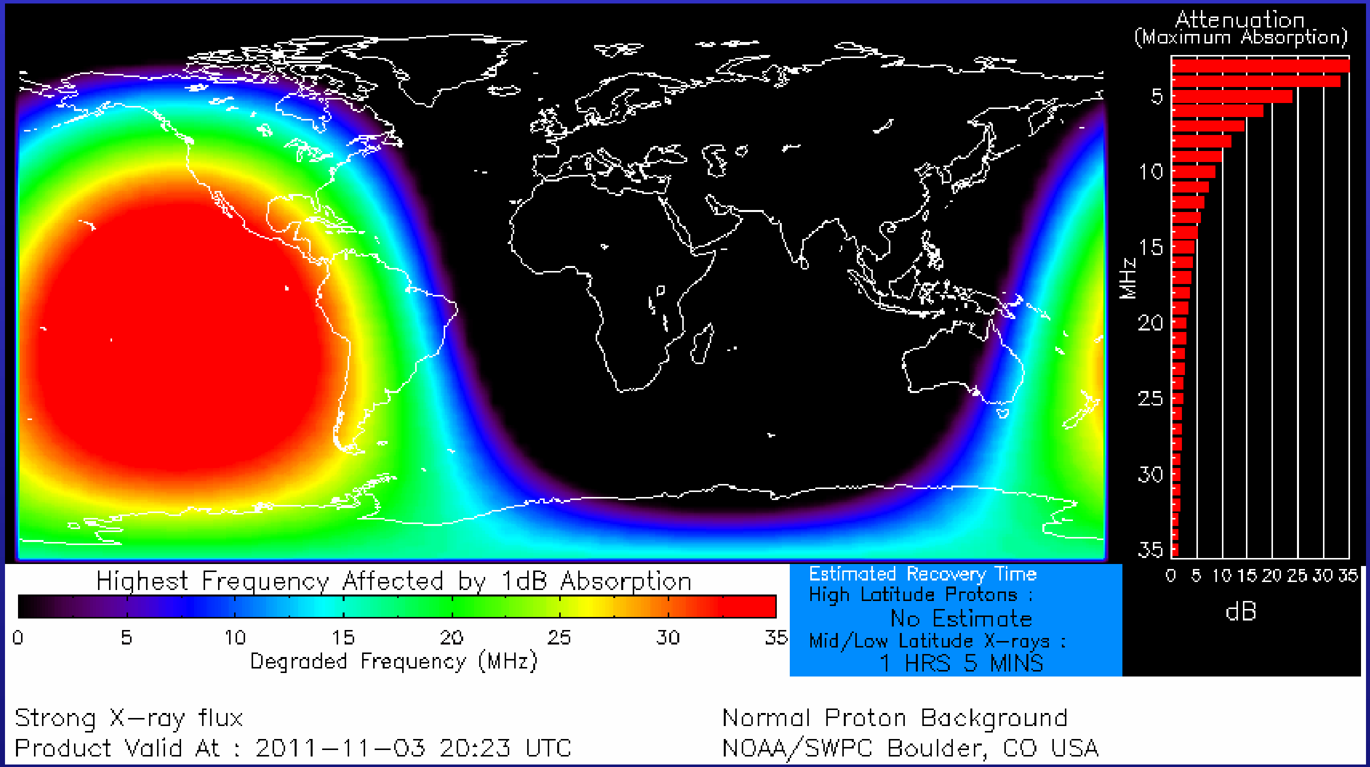
X-ray flare from late January 2012 at ~4UT.

NASA_SDO_131A_media.mp4

A solar flare is a violent explosion in the Sun's atmosphere releasing up to a total energy of 6×10^{25} Joules (this is equivalent to a ~14 billion megaton H-bomb).

Solar flares take place in the solar atmosphere, heating plasma to 10's of millions of degrees. Most flares occur in active regions around sunspots. Flares are powered by the sudden release of magnetic energy stored in the corona on the timescales of minutes to 10's of minutes.

Why should you care? X-Rays



Technology

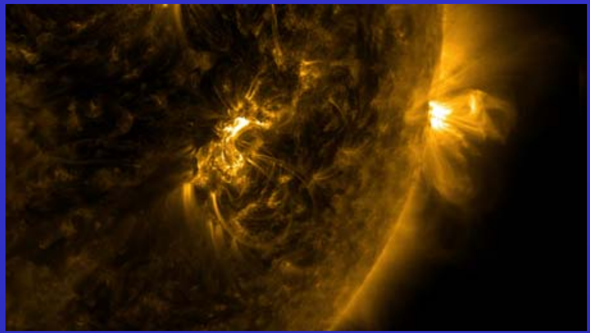
Impact

During the peak period of the X-ray flare (which lasts tens of minutes to an hour), the sunlit side of the Earth is being “zapped” by the waves. **This will degrade HF radio communications which are important to aviation!**

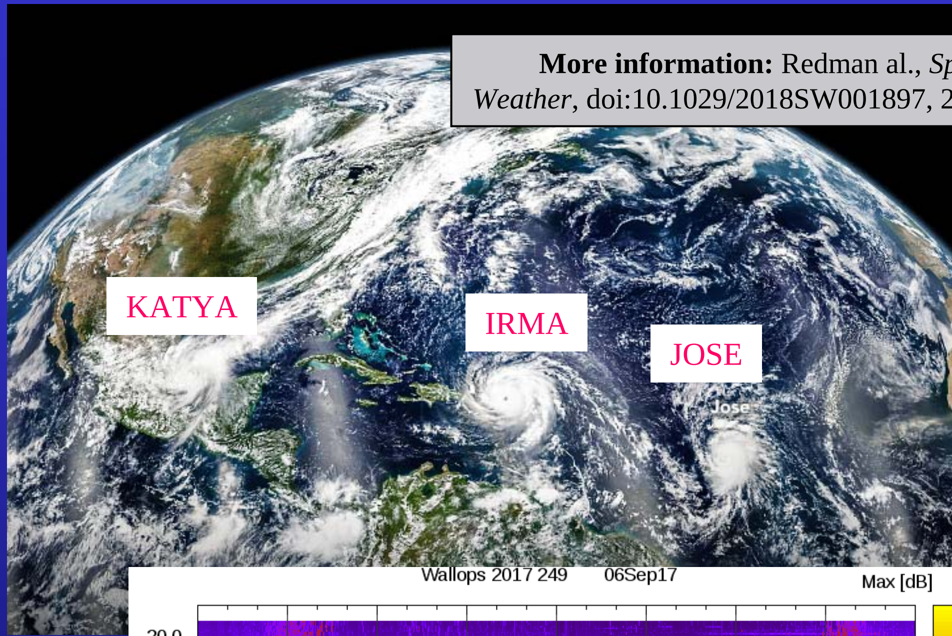
Technology

Impact

Why should you care?
X-Rays & HF communication

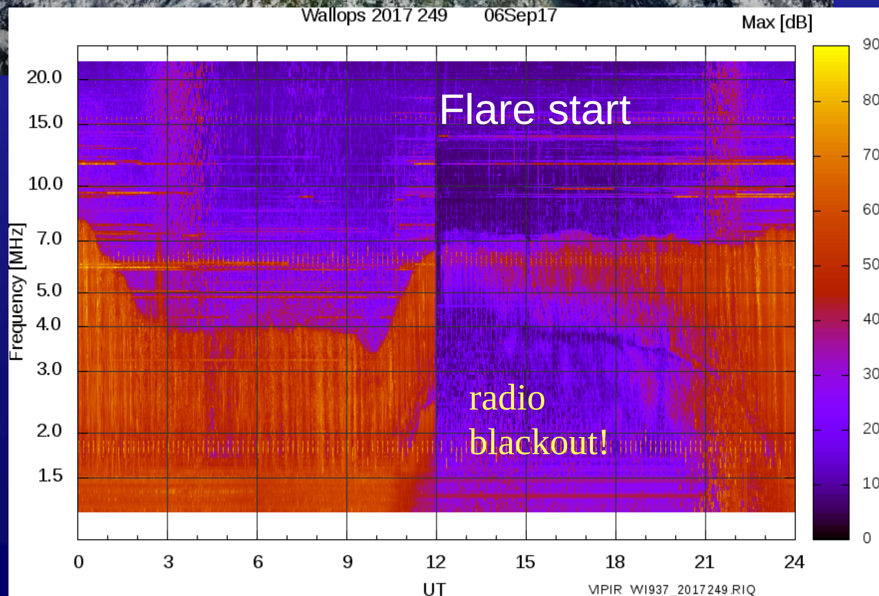


X9.3 and X2.2 solar flares on 6 September 2017 in extreme UV. *Credit:* ***NASA/GSFC/SDO***



More information: Redman al., *Space Weather*, doi:10.1029/2018SW001897, 2018

On 6 September 2017 three hurricanes were active in the Atlantic causing devastation to islands in the Caribbean.

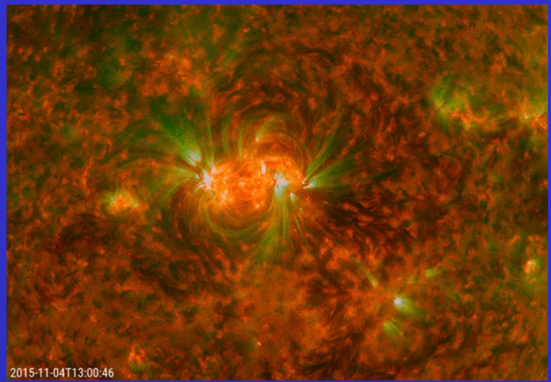


And then space weather kicked in on top of the extreme weather!

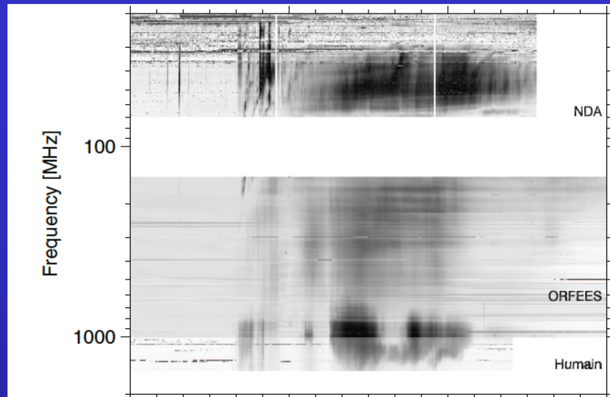
NOAA reports that high frequency radio, used by aviation, maritime, ham radio, and other emergency bands, was unavailable for up to eight hours. For example, civil aviation reported a 90-minute loss of communication with a cargo plane.

Technology Impact

Why should you care?
Solar Flare Radio Waves



M3.7 solar flares on 4 November 2015 in extreme UV.
Credit: ***NASA/GSFC/SDO***



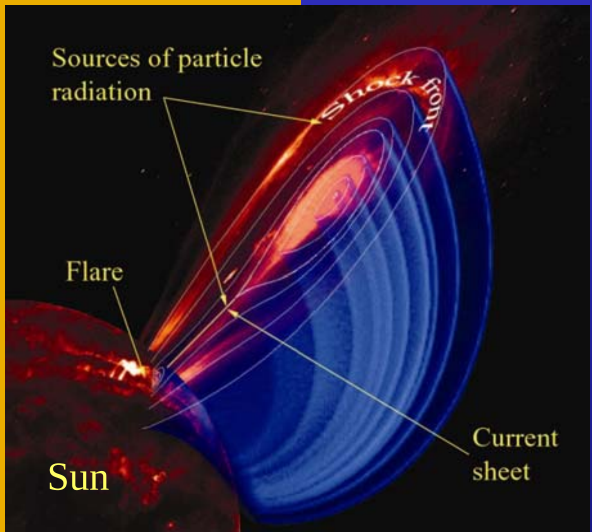
FROM: Marquéet al., *J. Space Weather Space Climate*, doi:10.1051/swsc/2018029, 2018

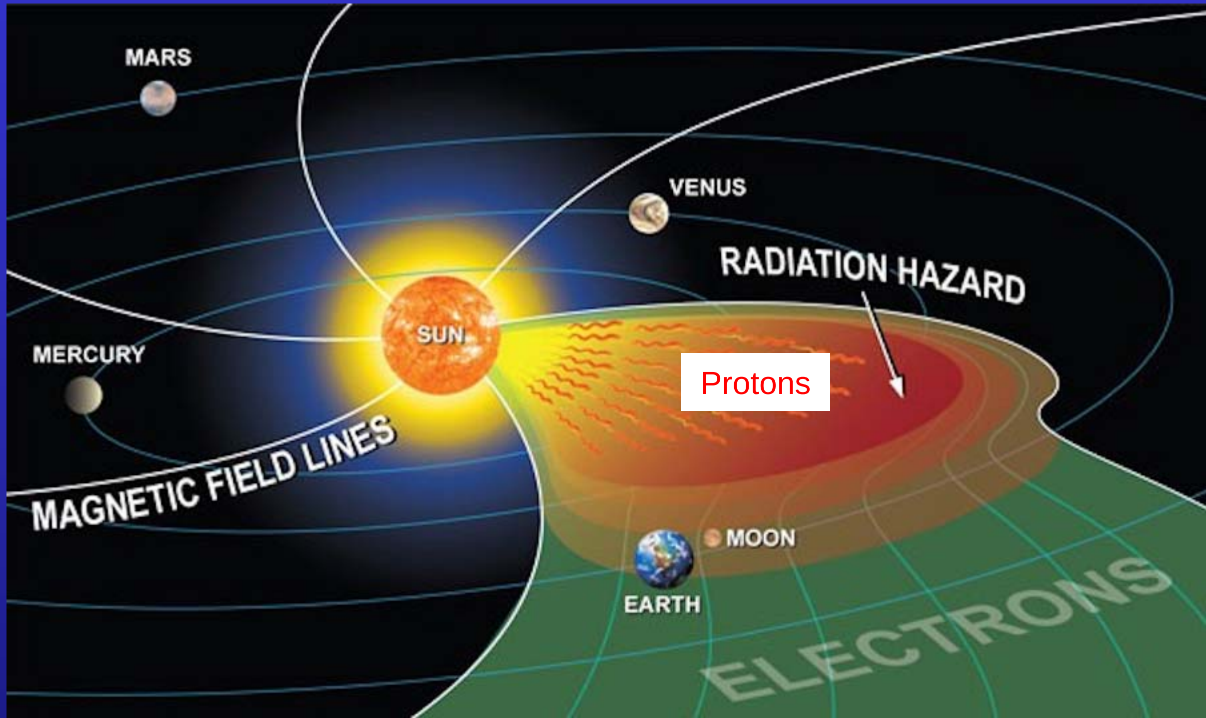
Solar Flares also release radio waves over a broad wavelength range. The medium sized X-ray flare on 4 November 2015 produced strong radio waves, which disrupted air traffic control radar systems in Belgium, Norway, Greenland and Sweden.

Sweden was badly affected for about an hour, and caused reduced aircraft movement as accurate information was not going to the controllers.

Radars affected by Solar produced "ghost echoes"

Solar Proton Events





The highest energy component of proton population which comes from the Sun is at relativistic levels. They have kinetic energies so high that they reach the Earth within minutes.

As these are charged particles, they are funneled into the polar atmosphere by the magnetic field of the Earth.

Solar

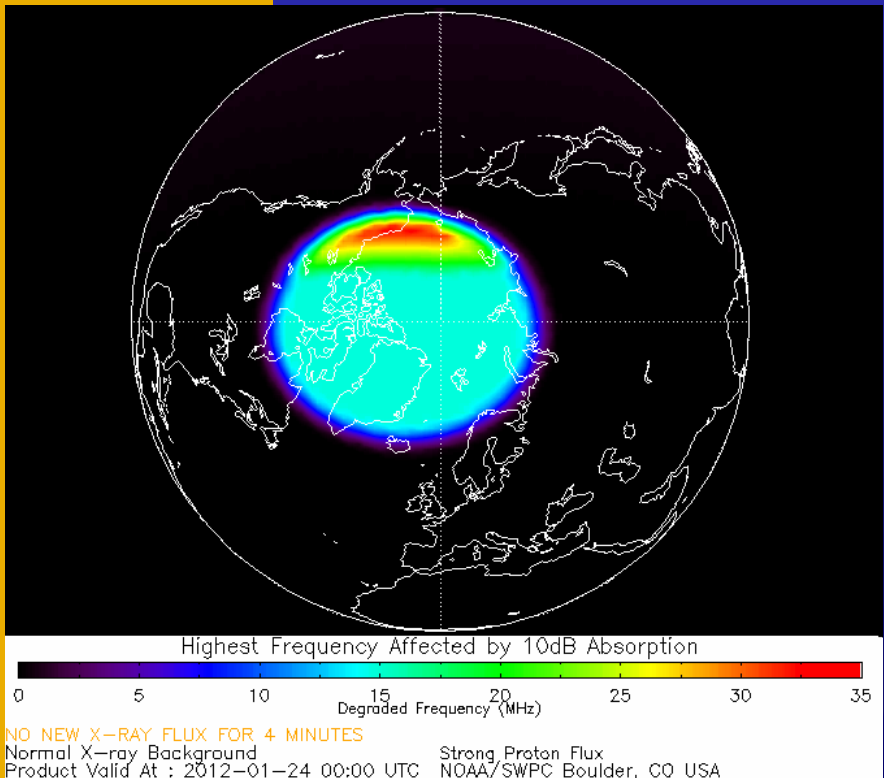
Forcing

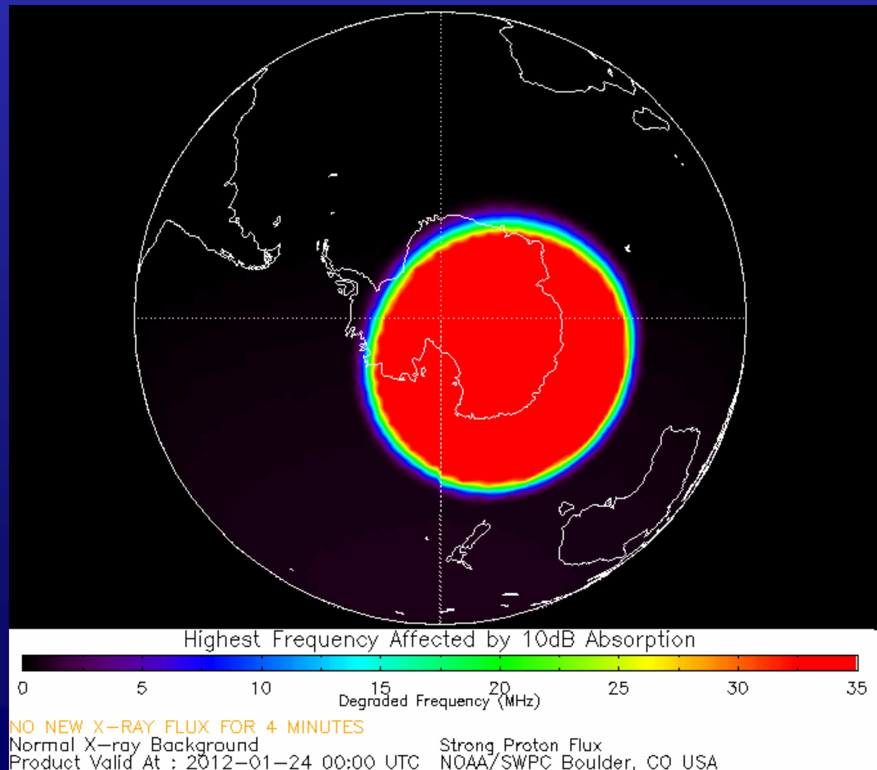
Why should you care? Solar Proton Events

Technology Impact

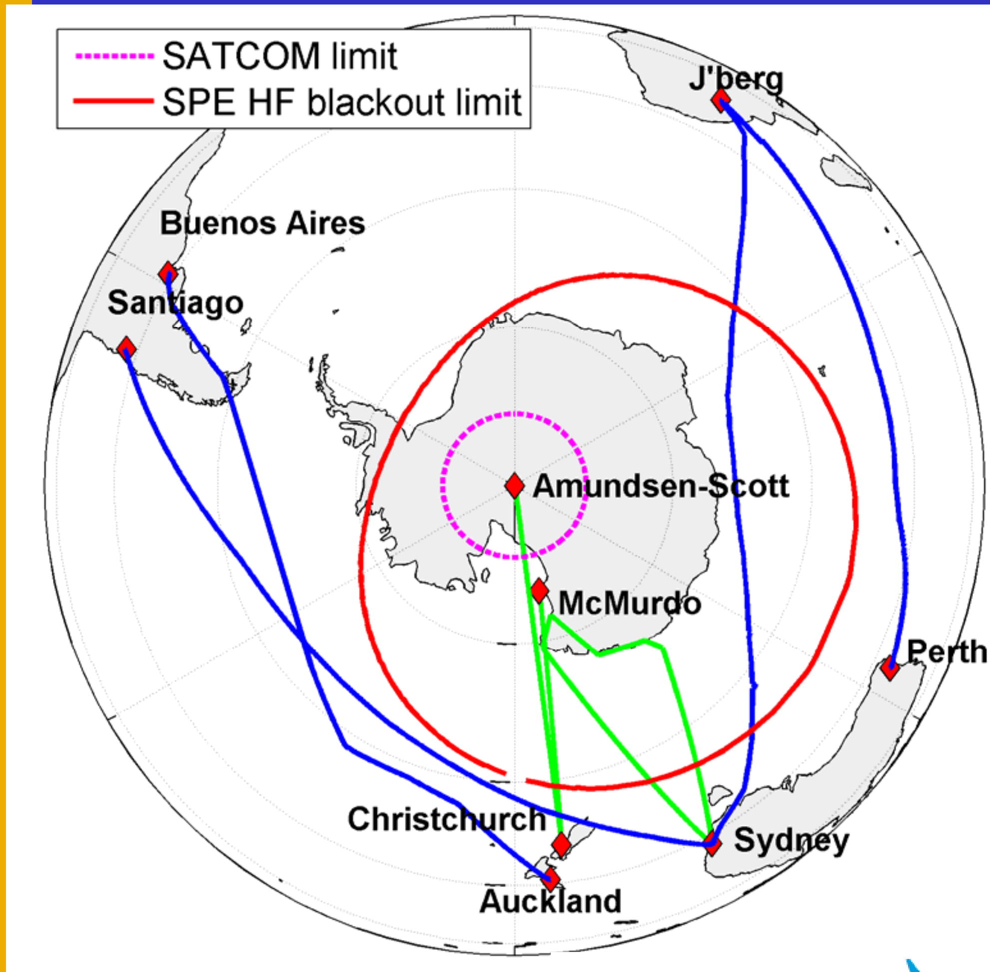
As these are charged particles, they are funneled into the polar atmosphere by the magnetic field of the Earth. Here they will degrade HF radio communications for several days, and increase radiation doses to people in aircraft. **Termed radiation storms or polar cap absorption.**

The example below is for 23-24 January 2012





Why should you care?
Solar Proton Events



Many airlines rely upon SATCOM, which uses geosynchronous communication satellites. This is impossible above 82° latitude.

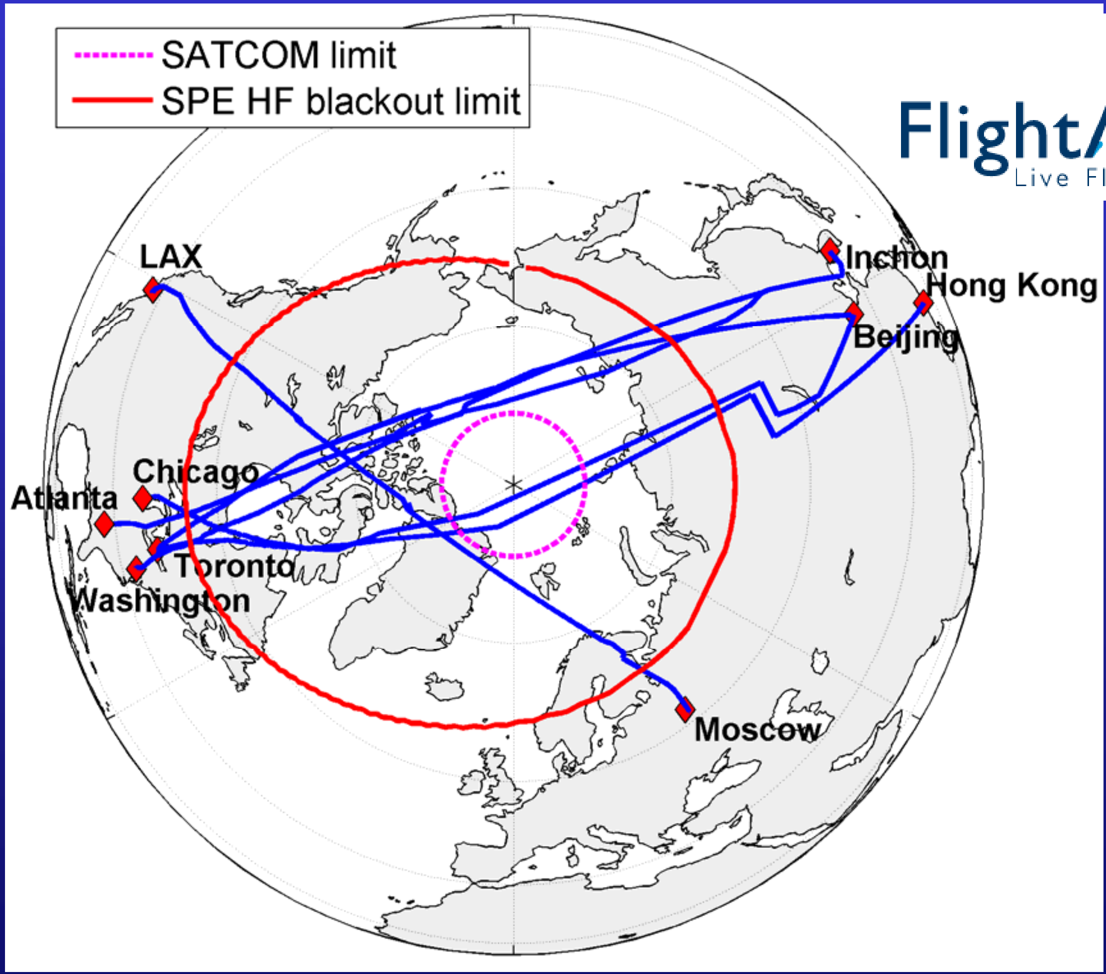
Beyond this High Frequency (HF) radio links are needed. Also HF radio is the primary backup communication system, and needs to be available!

This is <u>probably</u> less of an issue in the Southern Hemisphere, except for flights to and from the Antarctic.

Technology

Impact

Why should you care? Solar Proton Events



Clearly, this will be a bigger issue for the northern hemisphere, where the number of long-distance flights across the poles are growing fast.

Why should you care?
Solar Proton Events


THE WALL STREET JOURNAL. BUSINESS

Lockout Tests Union's Clout

Money From MF Global Feared Gone

Law Firms Keep Squeezing Associates

BUSINESS | JANUARY 24, 2012, 8:40 P.M. ET

Delta Reroutes Flights As Solar Storm Hits Earth

By DOUG CAMERON

The U.S. is bracing for the impact of the largest solar storm in almost a decade. Eric Holthaus joins the News Hub to discuss what to expect for travel and electrical devices. Photo: AFP / Getty Images.

Delta Air Lines Inc. said Tuesday that it was rerouting some transpolar flights between Asia and the U.S. to avoid the impact of the largest solar storm in almost a decade.

The Atlanta-based carrier said some flights to Detroit from Hong Kong, Shanghai and Seoul took a more southerly routing on overnight flights, though a spokesman said planes flew faster to keep schedules intact. Tuesday departures from the U.S. were

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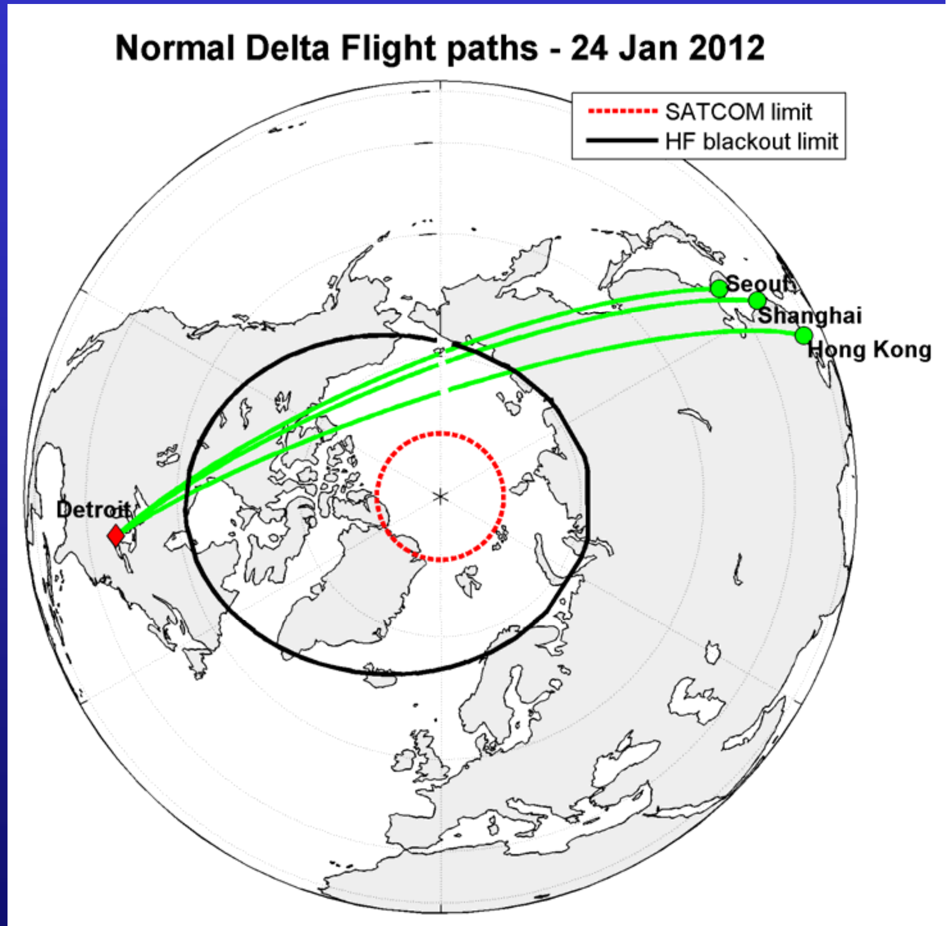
Money From MF Global Feared Gone

Citi Chairman Considers Departure

The Wall Street Journal 24 Jan 2012



Technology

Impact

This happened in January 2012– the US carrier Delta Airlines re-routed flights from Detroit to Seoul, Shanghai and Hong Kong onto routes that took them away from the poles! **Longer paths = more fuel = more money!**

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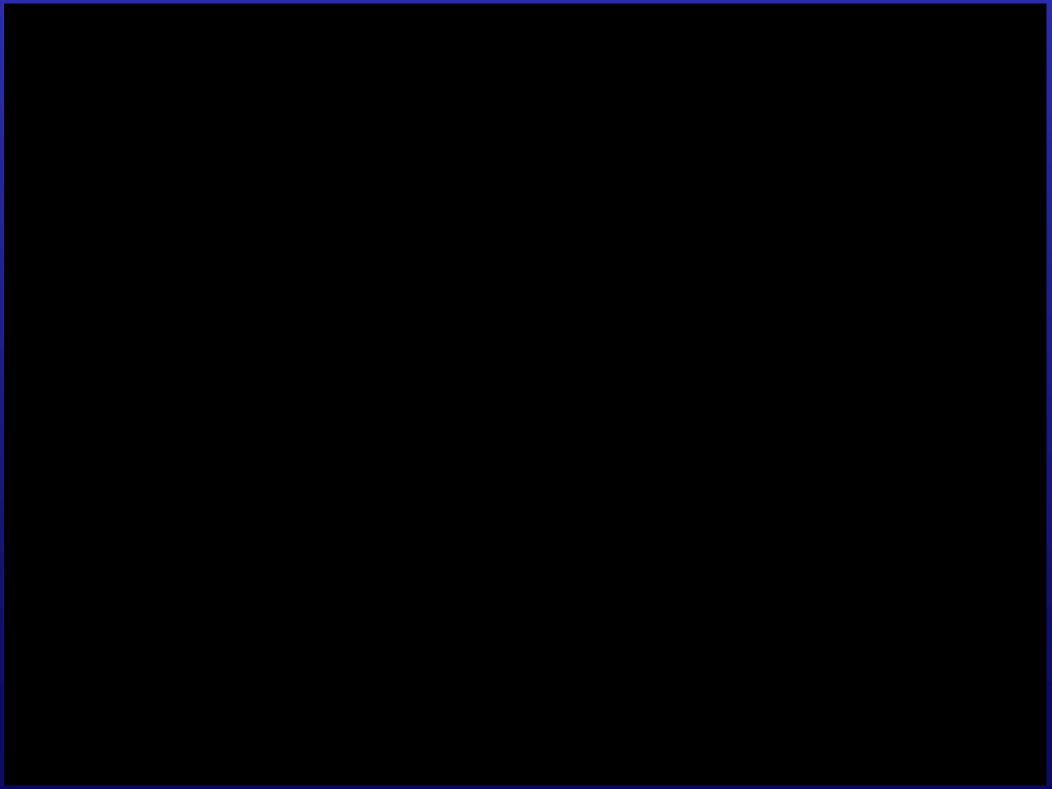
Coronal Mass Ejections

The ejection of billions of tons of matter into space by explosions on the Sun. The impact of these large plasma clouds on the Earth cause major geomagnetic storms.



View of the stream of solar wind coming from the Sun.

This movie is from 24-25 February 2014, and shows a Coronal Mass Ejection associated with a X4.9 solar flare.

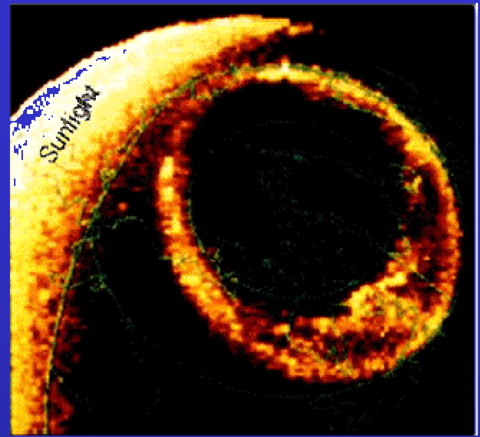
Credit: SOHO spacecraft

Solar

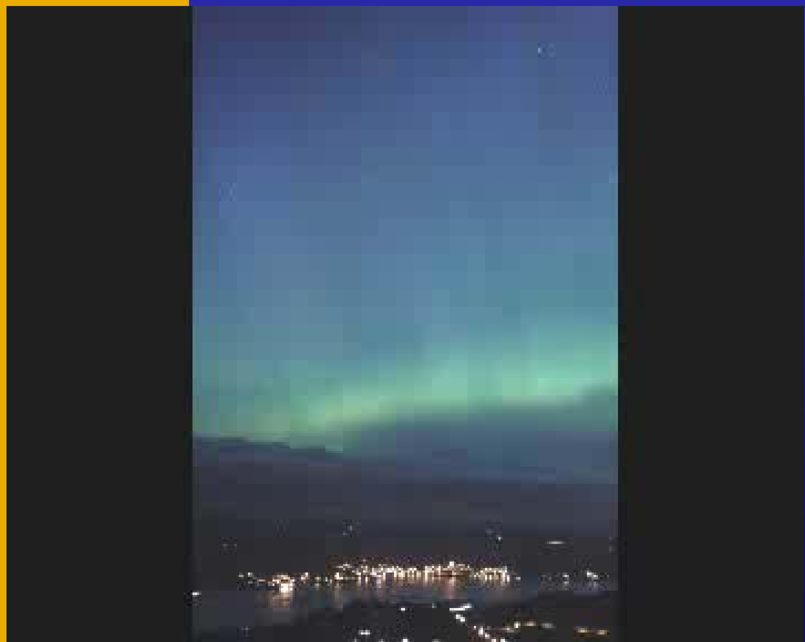
Forcing

Geomagnetic Storms

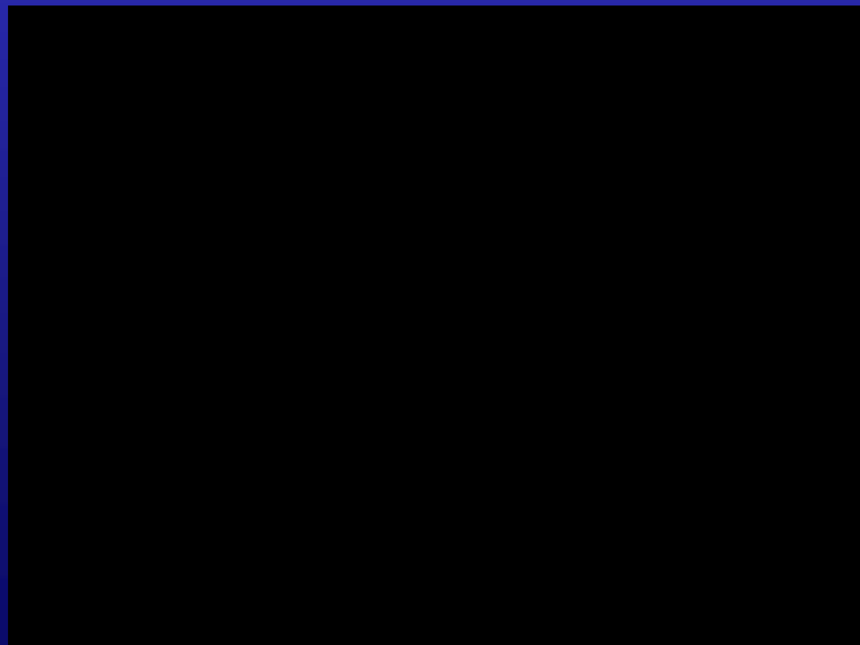
One consequence of a geomagnetic storm is an enhancement in aurora seen in the atmosphere above the north and south poles.



Auroral Oval seen from space.



Example of aurora seen over Dunedin (New Zealand) in November 2004.



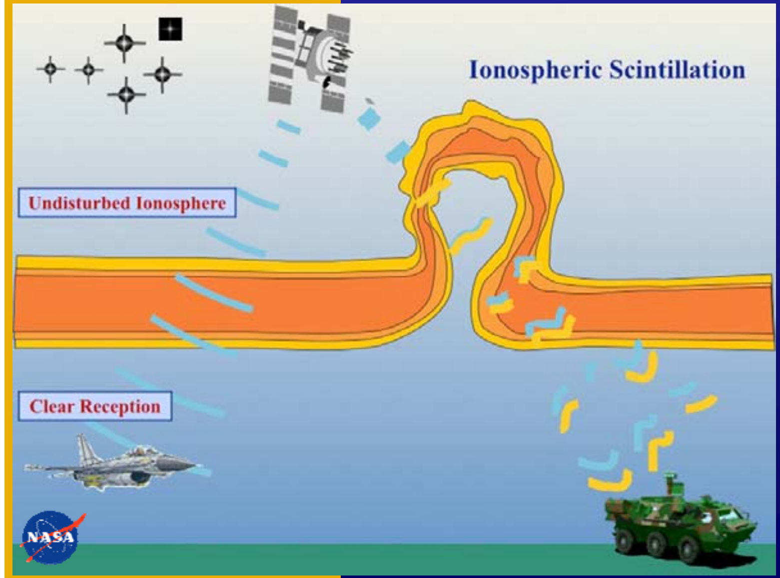
Example of Aurora Australis seen from the International Space Station (17 Sept 2011)

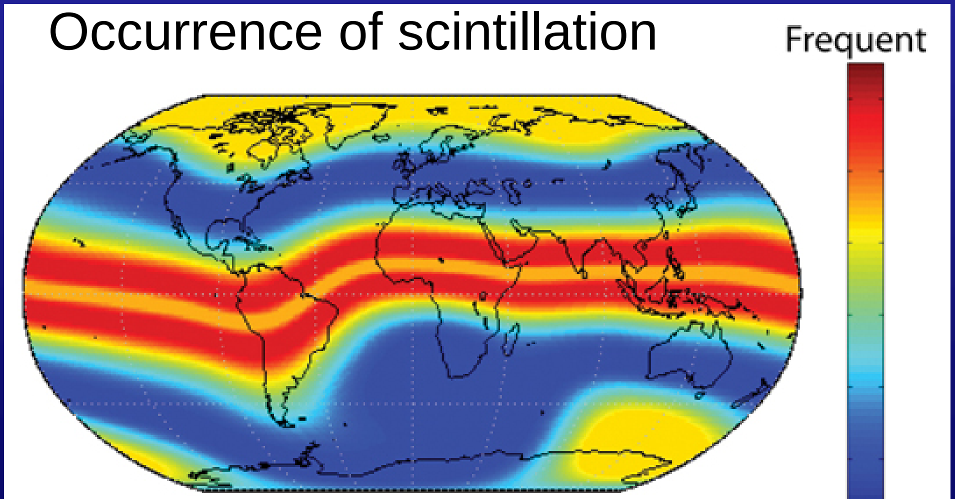
Plasma Bubbles

Technology
Impact

Ionospheric scintillation is the rapid modification of radio waves caused by small scale structures in the ionosphere (tens of m to tens of km). Scintillation events are linked to geomagnetic storms, but the relationship is complex!

- Severe scintillation conditions can prevent a GPS receiver from locking on (i.e. position and timing information lost).
- Less severe scintillation conditions reduce the position accuracy
- Can also impact UHF satellite communication systems.

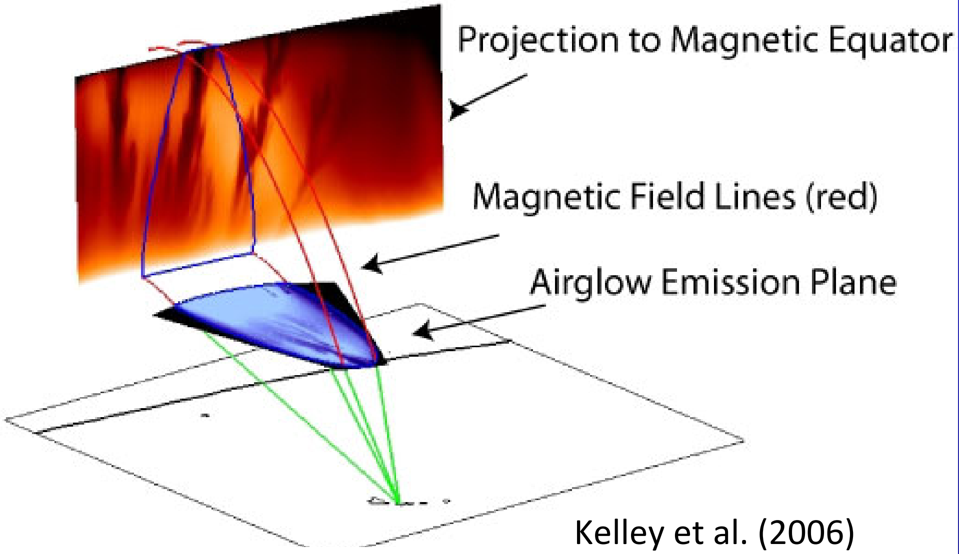




Kintner et al., *Inside GNSS*, Aug. 2009

Plasma Bubbles

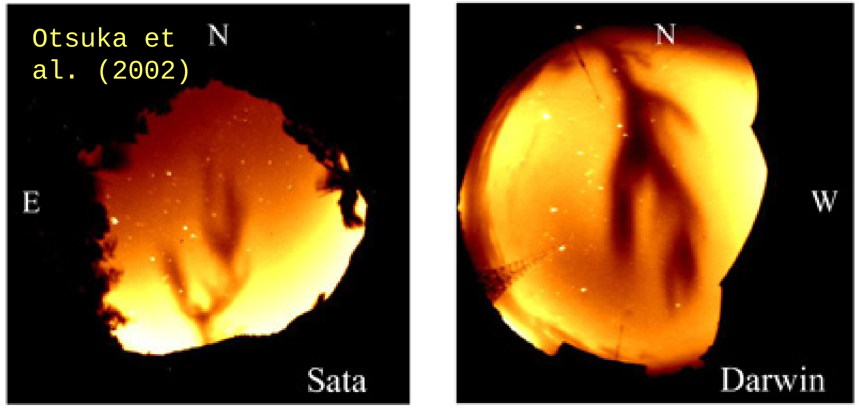
Technology Impact

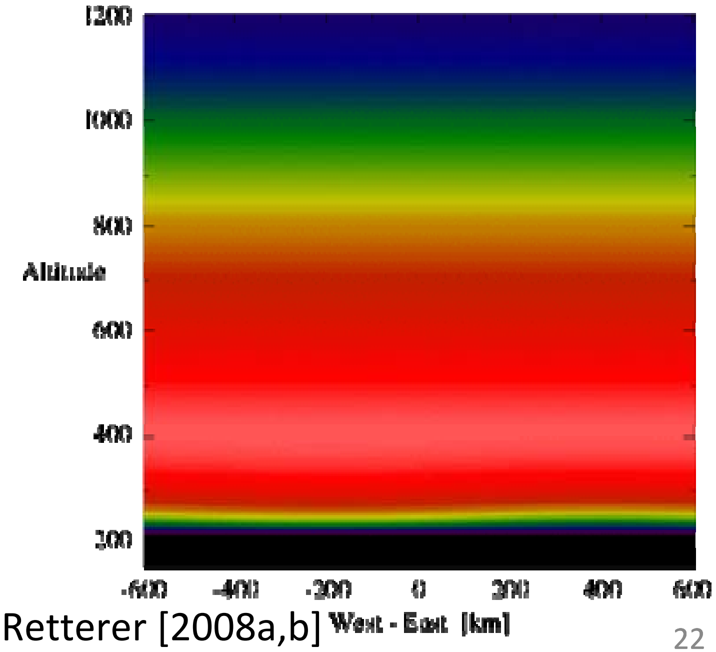


Vanimo PNG, 17 Mar 2000

All-sky cameras and numerical modelling

http://center.stelab.nagoya-u.ac.jp/site1/info_e/kagoshima.html





Retterer [2008a,b]

Generalised Rayleigh-Taylor instability:

$$\gamma = \frac{\Sigma_P^F}{\Sigma_P^E + \Sigma_P^F}\left(V_p - U_n^P - \frac{g_L}{\nu_{in}^{eff}}\right)\frac{1}{L_n} - R_T$$

Gravity

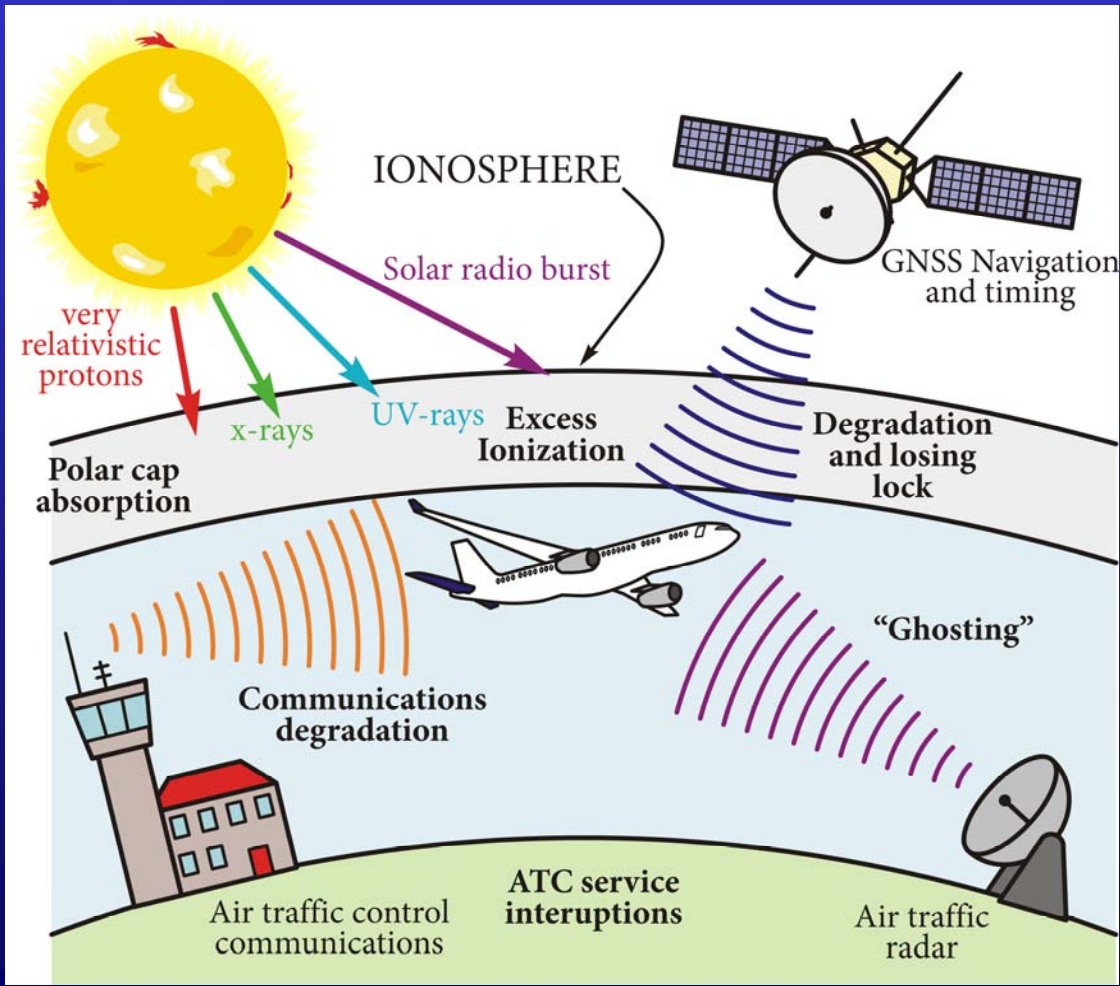
(Sultan *et al.*, 1996)

Upward plasma drift - prereversal enhancement after sunset

Technology
Impact

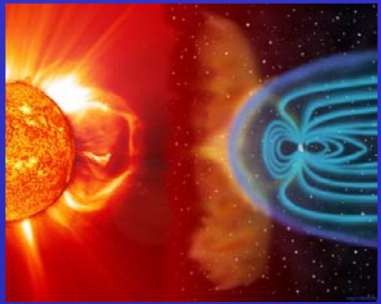
Aviation Impacts

Overview of the multiple routes by which space weather events can impact aviation.



Impact of a CME on the Earth's magnetic field

A large Coronal Mass Ejection (CME) can have great mass (10^{12} kg), and travel from the Sun at >500 km/s.



The blasts typically arrive at the Earth within 1.5-2 days, and cause large deformations of our protective magnetic field.

Credit: NASA

MHD simulation of the impact of a "Carrington-Class" CME

When a CME hits the magnetosphere, it is squashed, changing the field shape, setting up currents in space and on the ground, and triggering a geomagnetic storm.

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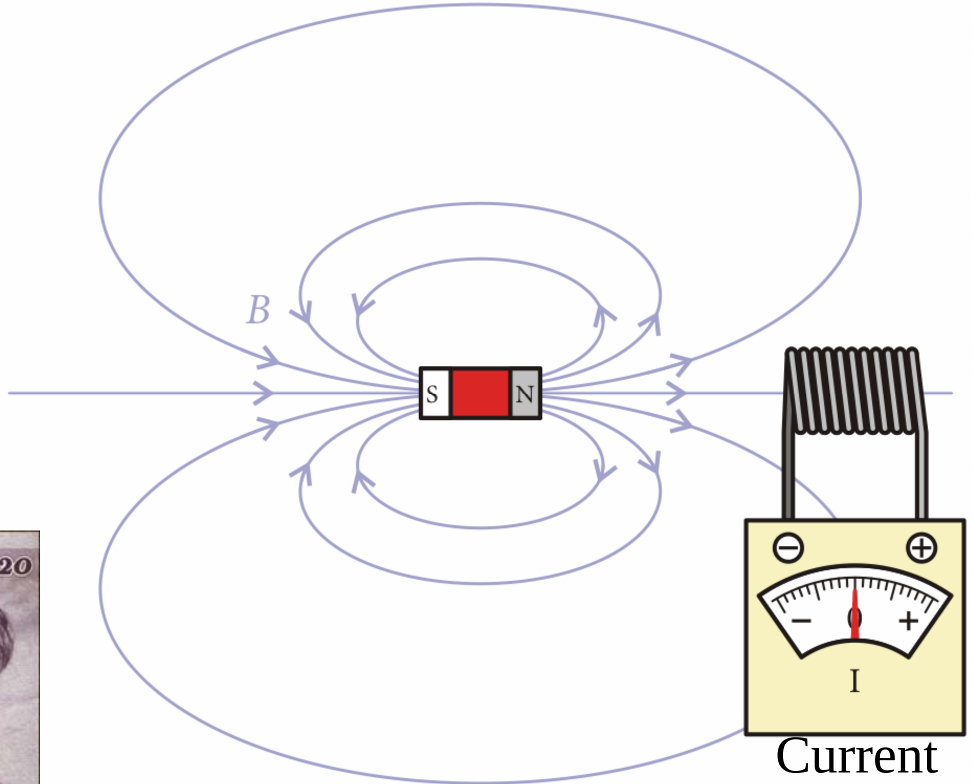
Faraday's Law of Induction

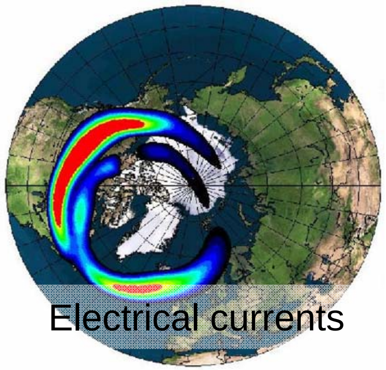
Technology Impact

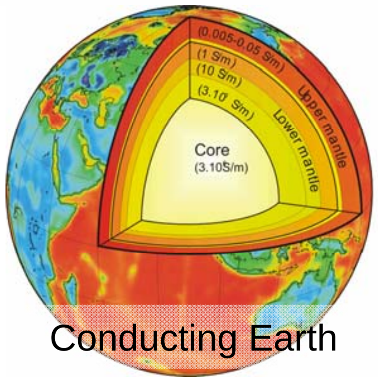
A moving magnet will produce a changing magnetic field.

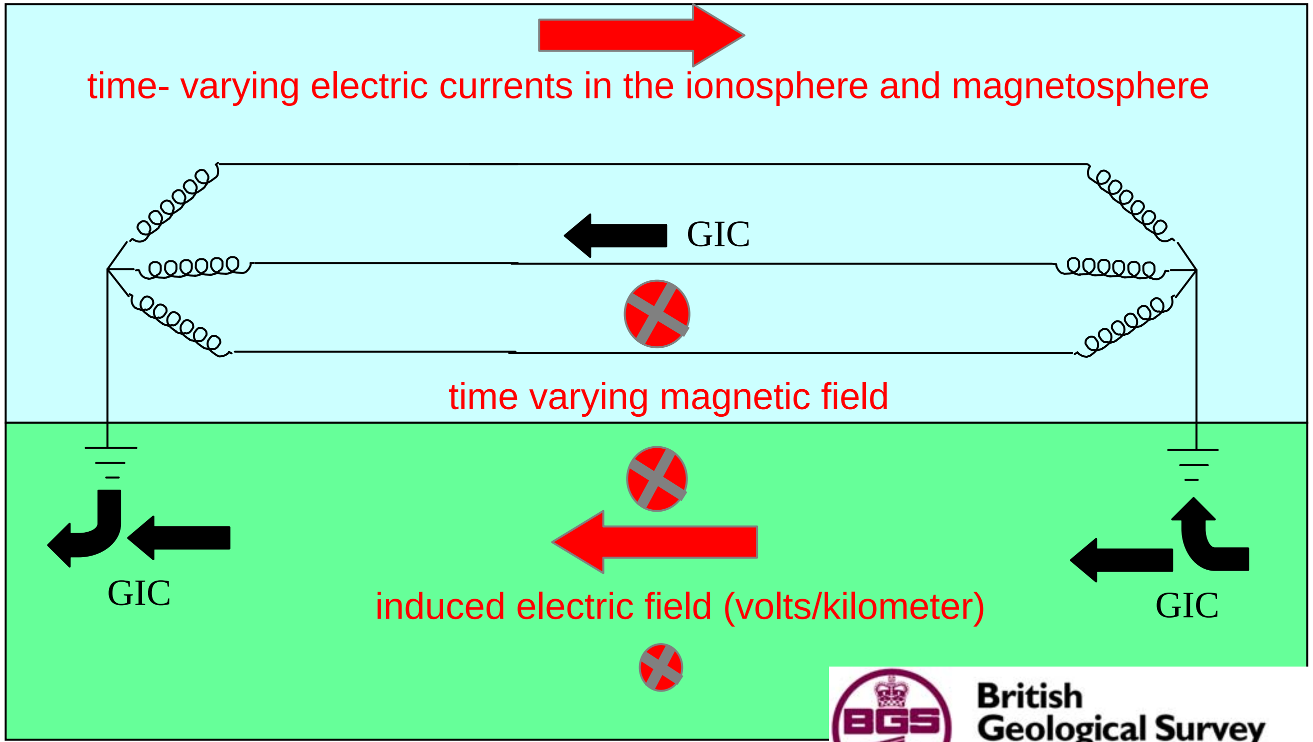


Famous physicist Michael Faraday demonstrated the law of induction, where a **changing magnetic field induces a current** in a conductor (like a wire, or the ground).

Why Does Space Weather Cause Grid Problems?







British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

Geomagnetically induced currents (GIC) cause

- Half-cycle saturation of transformers, voltage harmonics, overheating, increased reactive power demand, and/or drop in system voltage.
- Leading to **transformer burn-out** (in rare big storms) or **shortened transformer lifetimes** (due to many smaller storms).

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Technology Impact

Effect on power systems - local scale

These can be local to a specific transformer in a given substation, potentially destroying a transformer.

New Jersey, March 1989.
USA

courtesy Metatech

South Africa, Oct 2003

GIC = Geomagnetically induced currents

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Effect on power systems - regional scale

Most dramatic GIC example to date is the "great magnetic storm" of March 1989.

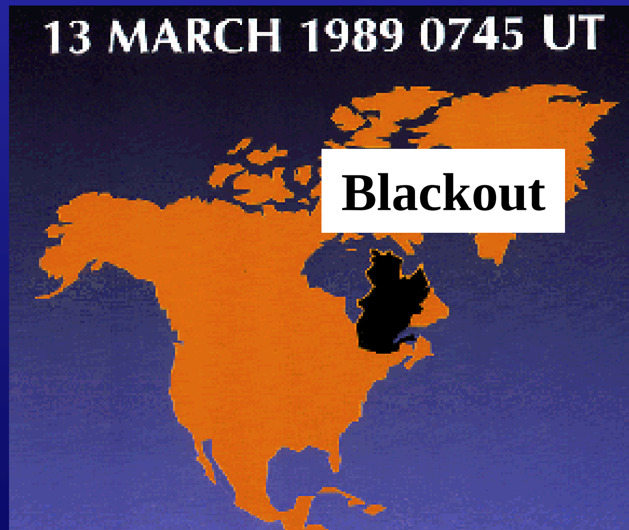
Technology

Impact

Hydro-Québec's (TransÉnergie) electric transmission system collapsed in 92 seconds.

- ~ 9 million people were left without electricity
- blackout lasted around nine hours for most places
- some locations were in the dark for days

Over 200 significant power grid problems across the continent.



GIC = Geomagnetically induced currents

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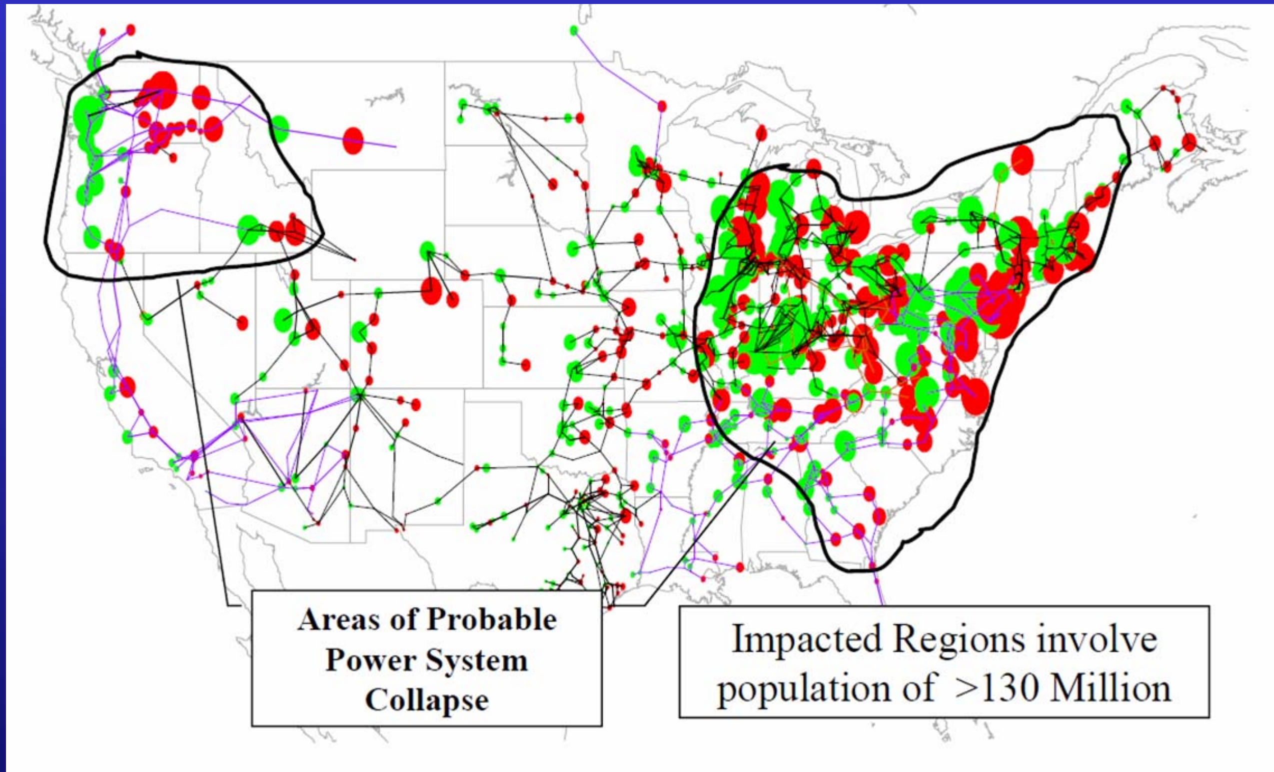
Should we worry for the biggest storms?

Modelling for the USA for a “extreme” sized geomagnetic storm predicted destruction of >300 primary transformers (out of 2,100 total):

* Replacements might take a year or more
* Cost in the first year as high as US$2 trillion



Technology

Impact

Source: Baker, D. N., et al. (2008), Severe Space Weather Events: Understanding Societal and Economic Impacts, 144 pp., National Academies Press, Washington, D. C., USA.

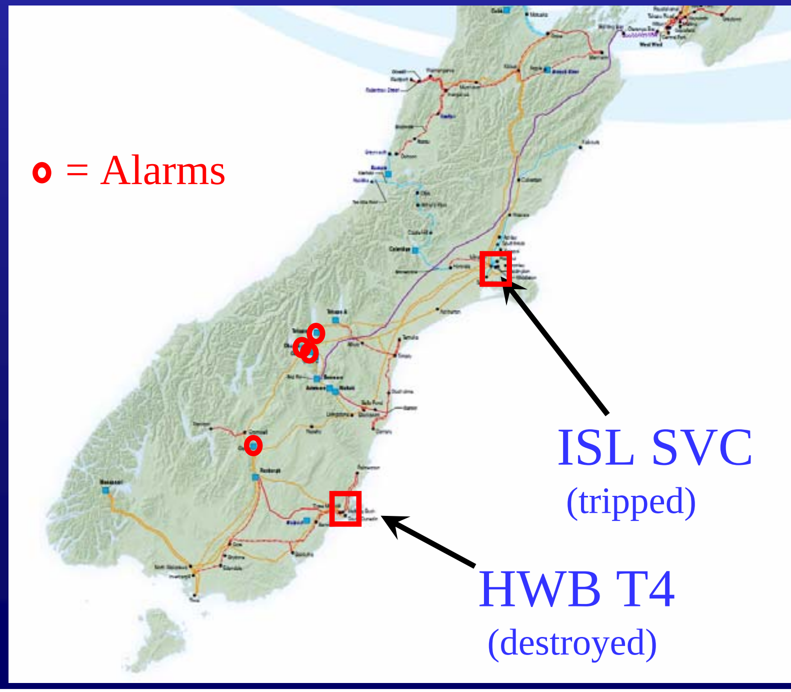
Much action stimulated in the USA. In October 2015, the **National Space Weather Strategy** & **National Space Weather Action Plan** released.

Effects of GIC on power systems – NZ!!

A large geomagnetic storm started on 6 November 2001 at ~2:53pm LT (1:53am UT). At this time HWB T4 (Dunedin) tripped, as did systems at ISL (Christchurch). Alarms occurred at multiple locations across the South Island.

The transformer at Dunedin / Halfway Bush (HWB T4) suffered a major internal flashover. A subsequent internal inspection found the transformer was beyond repair - it was subsequently written off (~$2 million value in 2016 NZD).

Halfway Bush Substation, Dunedin.



GIC risk mitigation research in NZ

MINISTRY OF BUSINESS, INNOVATION & EMPLOYMENT
HIKINA WHAKATUTUKI

Solar Tsunamis: Mitigating Emerging Risks to New Zealand's Electrical Network

New Zealand Team

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TRANSPOWER

MetService

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NATURAL ENVIRONMENT RESEARCH COUNCIL

British Antarctic Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

Project ran
1 October 2015 to
30 September 2018

Extreme Space Weather – all at once!

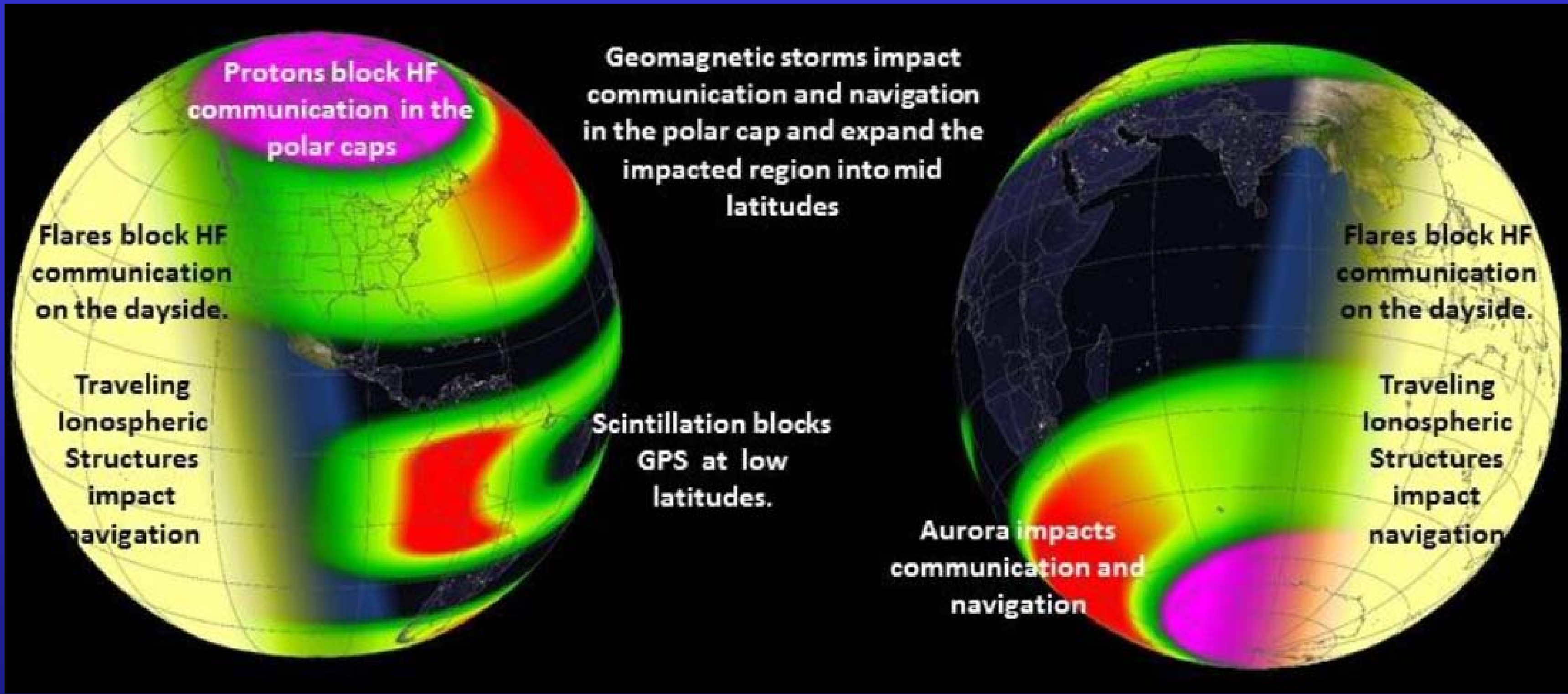

Image from Rodney Viereck (NOAA SWPC)

In the event of an extreme space weather event (maybe once every 100 to 200 years) all of the “bad” space weather impacts could happen more or less simultaneously!

Space Weather is another hazard

Landslips

Floods

Tsunami

Extreme Wind

Earthquakes

Volcanoes

Hazard Images from:
www.eqc.govt.nz/be-prepared
& www.metservice.com

In New Zealand we are used to thinking about a significant number of natural hazards - "High Impact, Low Probability" (HILP) events. For example, Transpower plans for 1:2500 year seismic events.

Space Weather

In our modern society, we must now also consider space weather.

Technology

Impact

Space Weather is another hazard

Cabinet Office

https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/644968/UK_National_Risk_Register_2017.pdf

Met Office

Industry	Impact
Energy	Power blackouts Damage to grid infrastructure
Satellite	Damage to satellites Impacts on performance
Communications	Loss of long distance radio communication
Aviation	Disruption to HF comms and high latitude routes Additional radiation doses at high altitude
Marine	Disruption to critical navigation systems
Road transport	Disruption of GNSS
Rail transport	Disruption of GNSS

Last updated: 20 May 2016

The impact of extreme Space Weather now appears on the National Risk Register for the United Kingdom (since 2013) – and actually is now also on the register for many other countries. The UK Government directed the UK MetOffice to provide forecasting for space weather.

My groups primary support has come from:

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SEVENTH FRAMEWORK PROGRAMME

MINISTRY OF BUSINESS, INNOVATION & EMPLOYMENT
HIKINA WHAKATUTUKI

FULBRIGHT
NEW ZEALAND
TE TŪĀPAPA MĀTAURANGA O AOTEAROA ME AMERIKA

Department of Physics
SPACE PHYSICS GROUP
University of Otago

Craig Rodger gives a talk on Space Weather at "The Sunroom", a public art installation [20 June 2017].

Thankyou for listening

Is there time for questions?