SPACE WEATHER

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7th July 2017

What is space weather?

U.S. National Space Weather Plan:

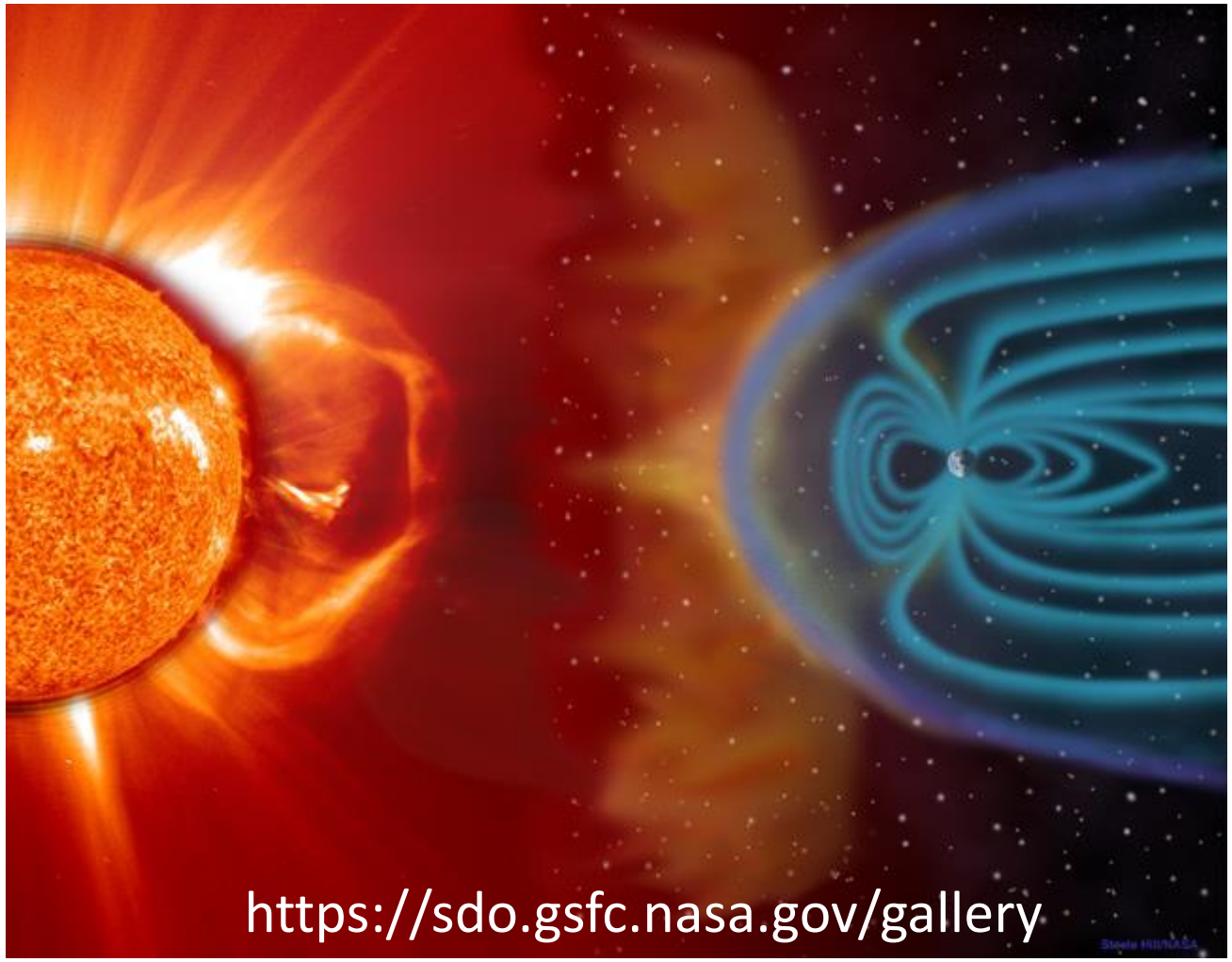
'...space weather refers to conditions on the Sun and in the solar wind, magnetosphere, ionosphere, and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and that can affect human life and health...'

Selected reviews used in this lecture:

R. Schwenn, *'Space Weather: The Solar Perspective'*, Living Rev. Solar Phys., 3, (2006), 2

T. Pulkkinen, *'Space Weather: Terrestrial Perspective'*, Living Rev. Solar Phys., 4, (2007), 1

Space weather: scheme



Sun
- Phenomena

[solar physics]

escape & travel

IP space [heliosphere studies]
- solar wind
- (cosmic rays…)

arrival & effect

L1
- satellites

[engineering]

Earth
- Magnetosphere
- Atmosphere
- Ground

[terrestrial studies]

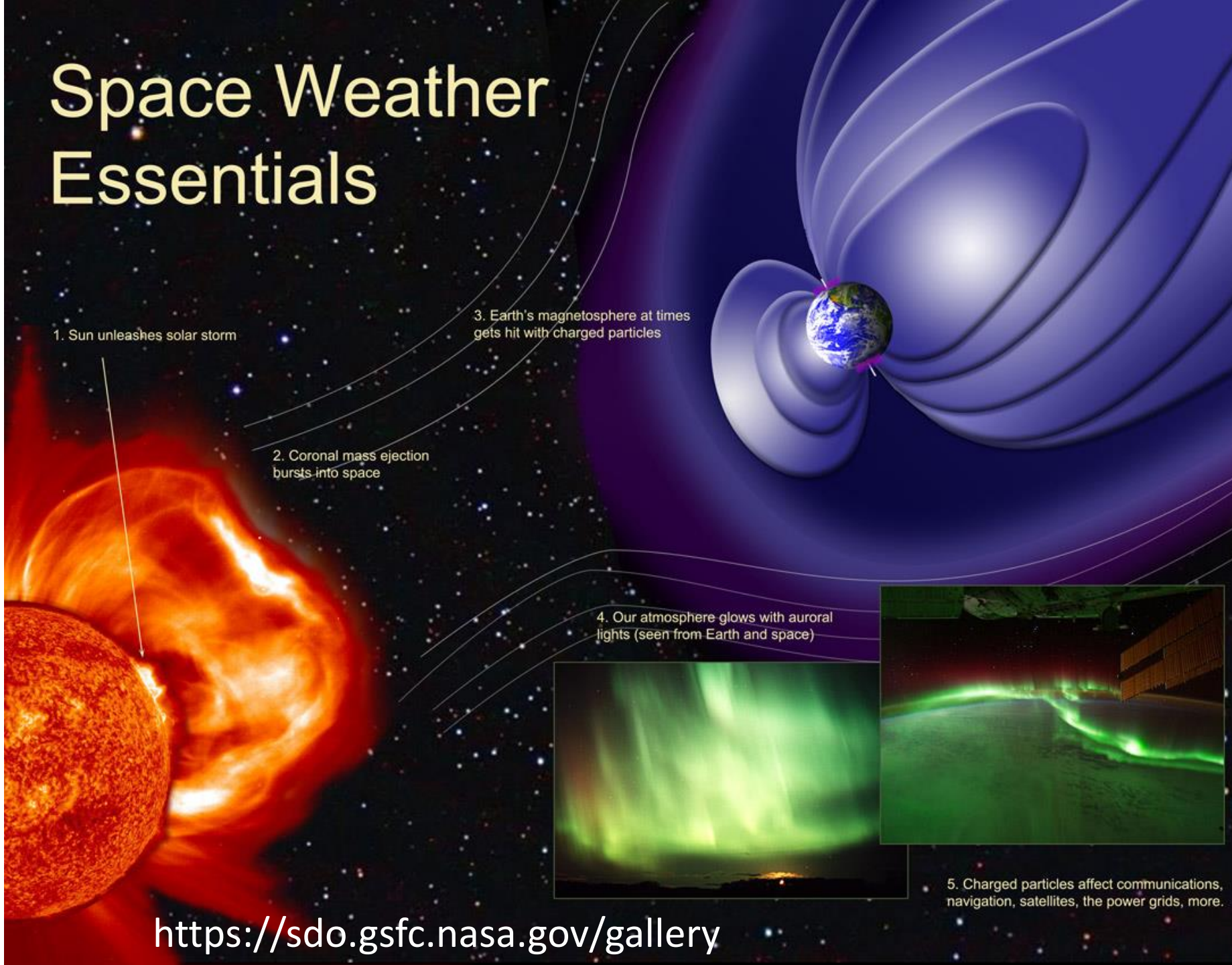
Space weather

Negative effects

- Satellites
- Ground-based systems
- Human health

Positive effects

- Auroras



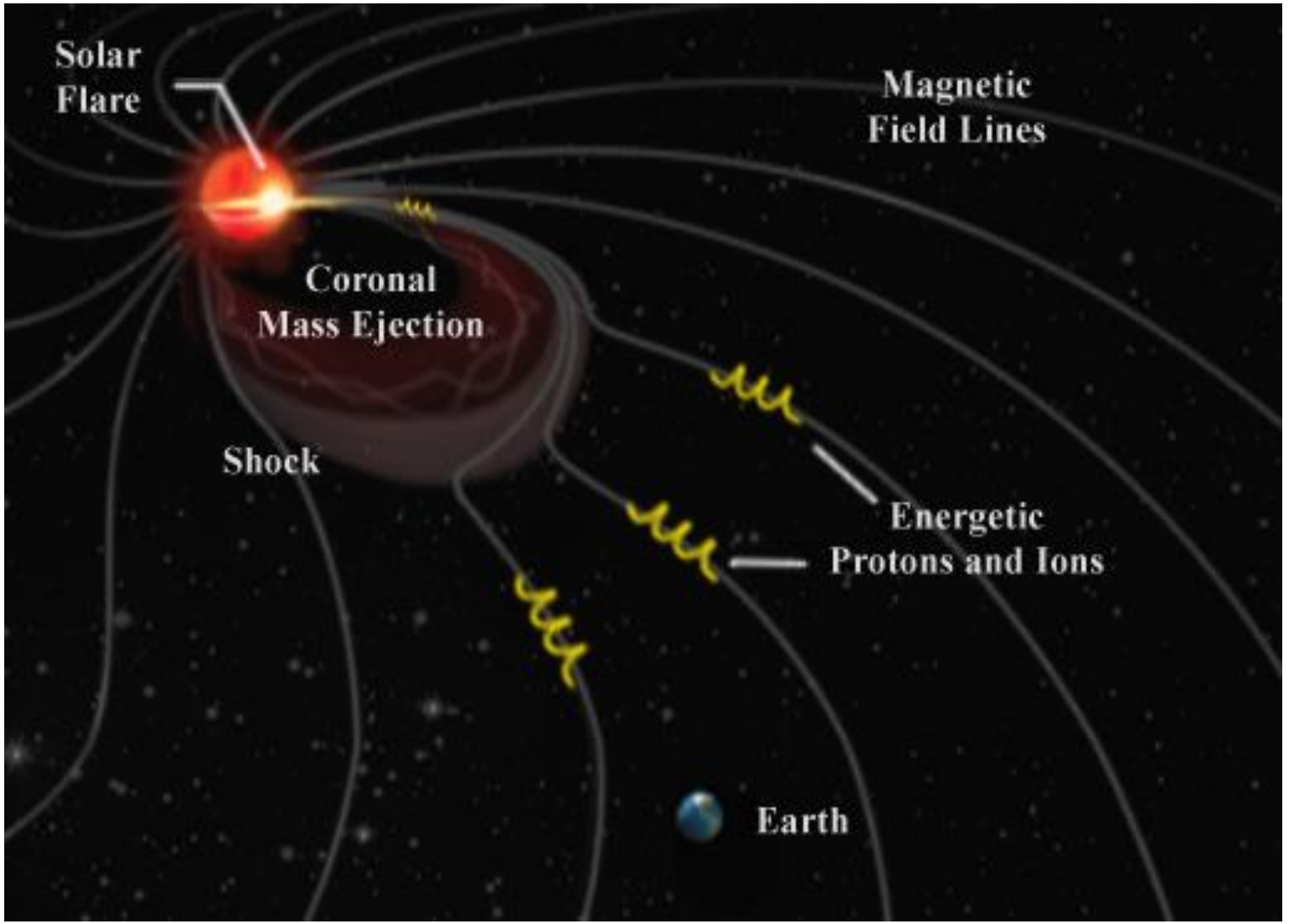
Space weather causes: solar eruptive phenomena

I. Solar wind & IMF

II. Flares

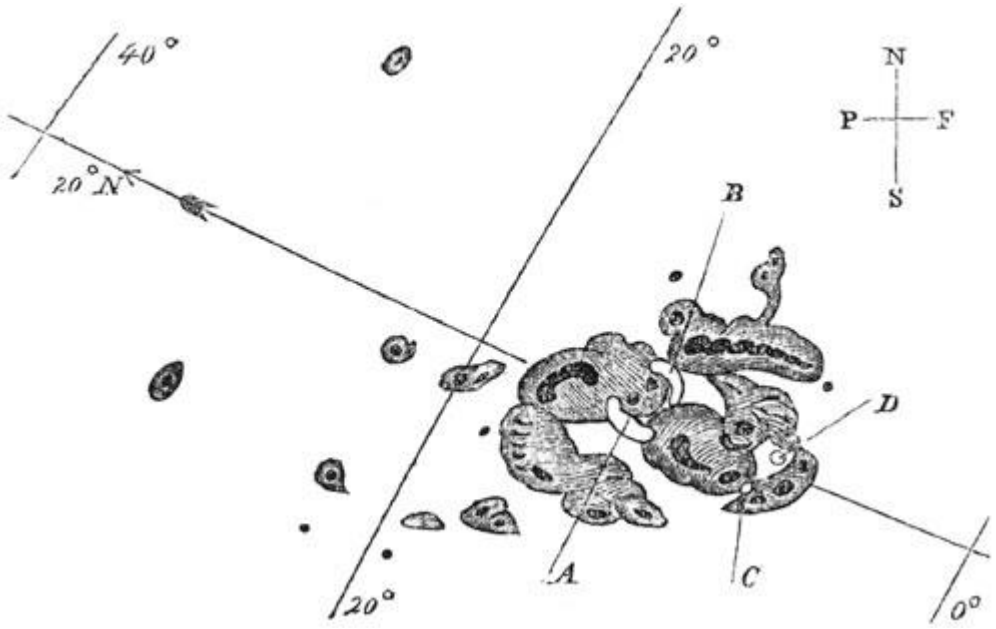
III. Coronal mass ejections

IV. Solar energetic particles



http://spaceweather.uma.es/images/figura1bc.JPG

History: Carrington-Hodgson event



Richard Carrington drawing

1 September 1859: large white-light flare flare
Carrington and Hodgson: 2 papers in MNRAS

1-2 Sept 1859: largest recorded geomagnetic storm
estimates range between -800 nT and -1750 nT

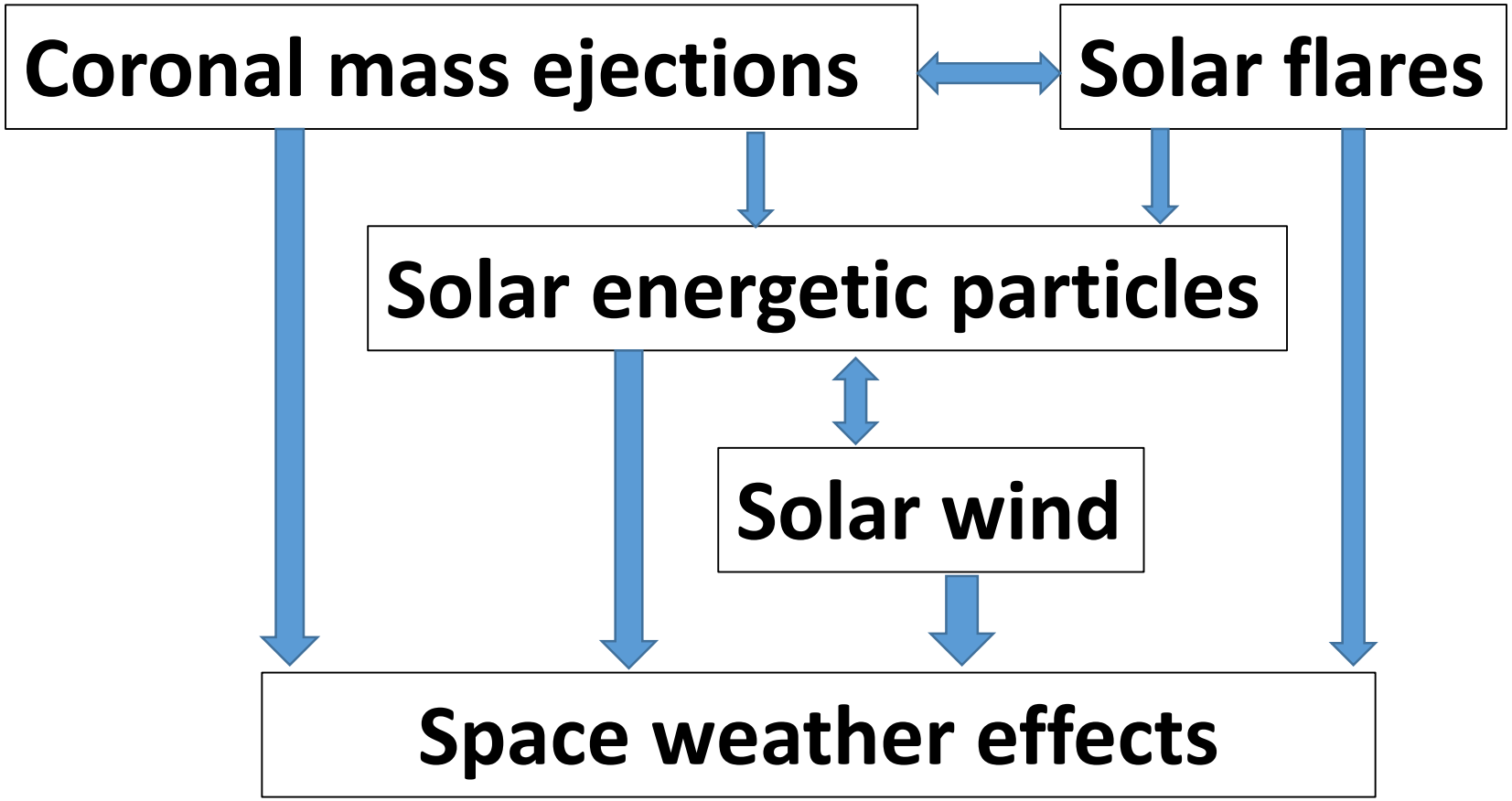
Carrington supposes a link, but
'one swallow does not make the spring'!

Auroras seen as low as tropical & equatorial latitudes!

Failure of telegraph systems!

Nowadays estimation for economical losses
due to Carrington-like event: up to trillion dollars!

Scheme

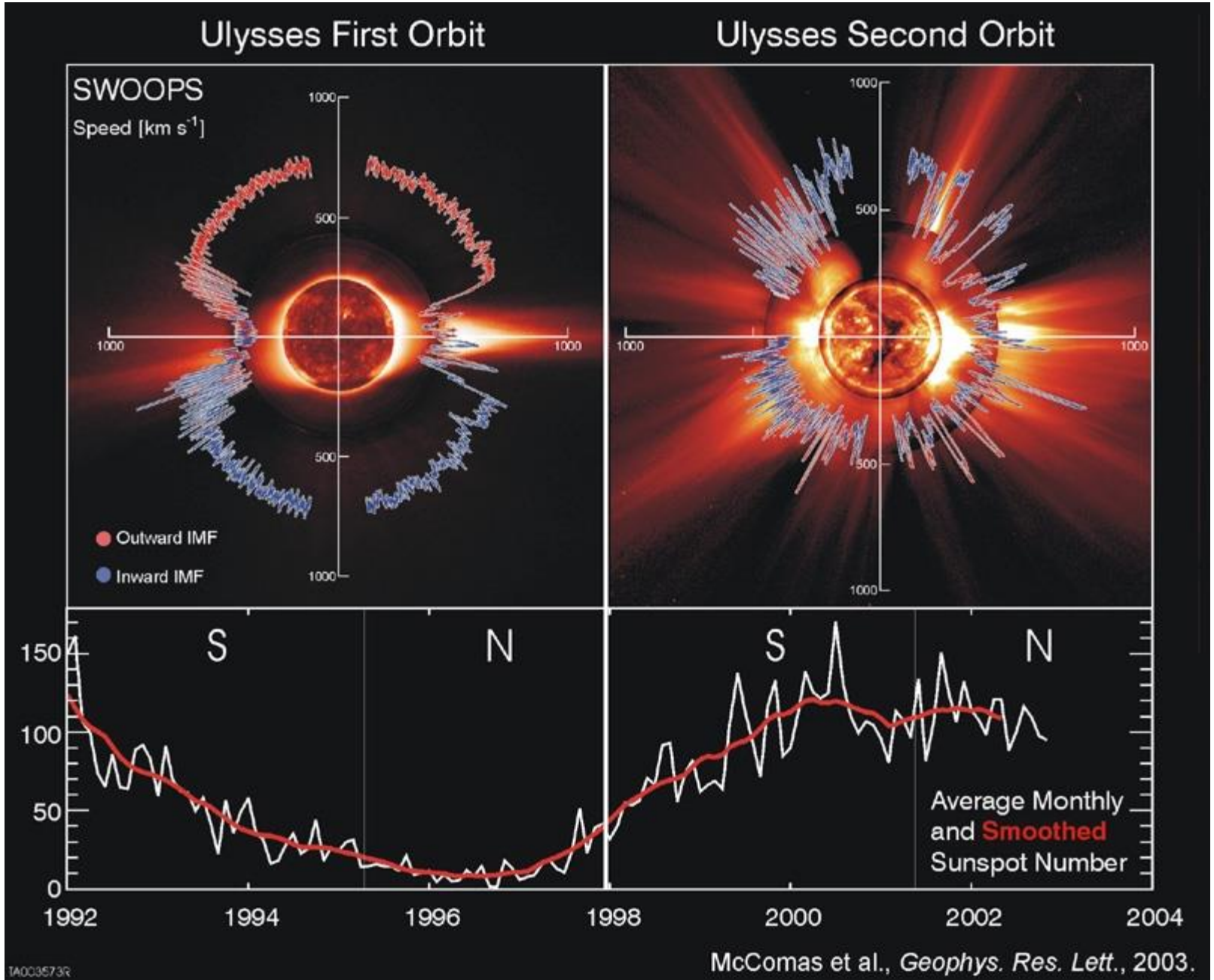

Coronal mass ejections
Solar flares
Solar energetic particles
Solar wind
Space weather effects

Space weather causes: solar wind

- stream of charged particles released from solar corona

- suggested to explain comet tails (eg. Eddington 1910; Biermann 1950s)

- termed by Eugene Parker (1958)



Fast speed

- from coronal holes;

solar poles

- low density

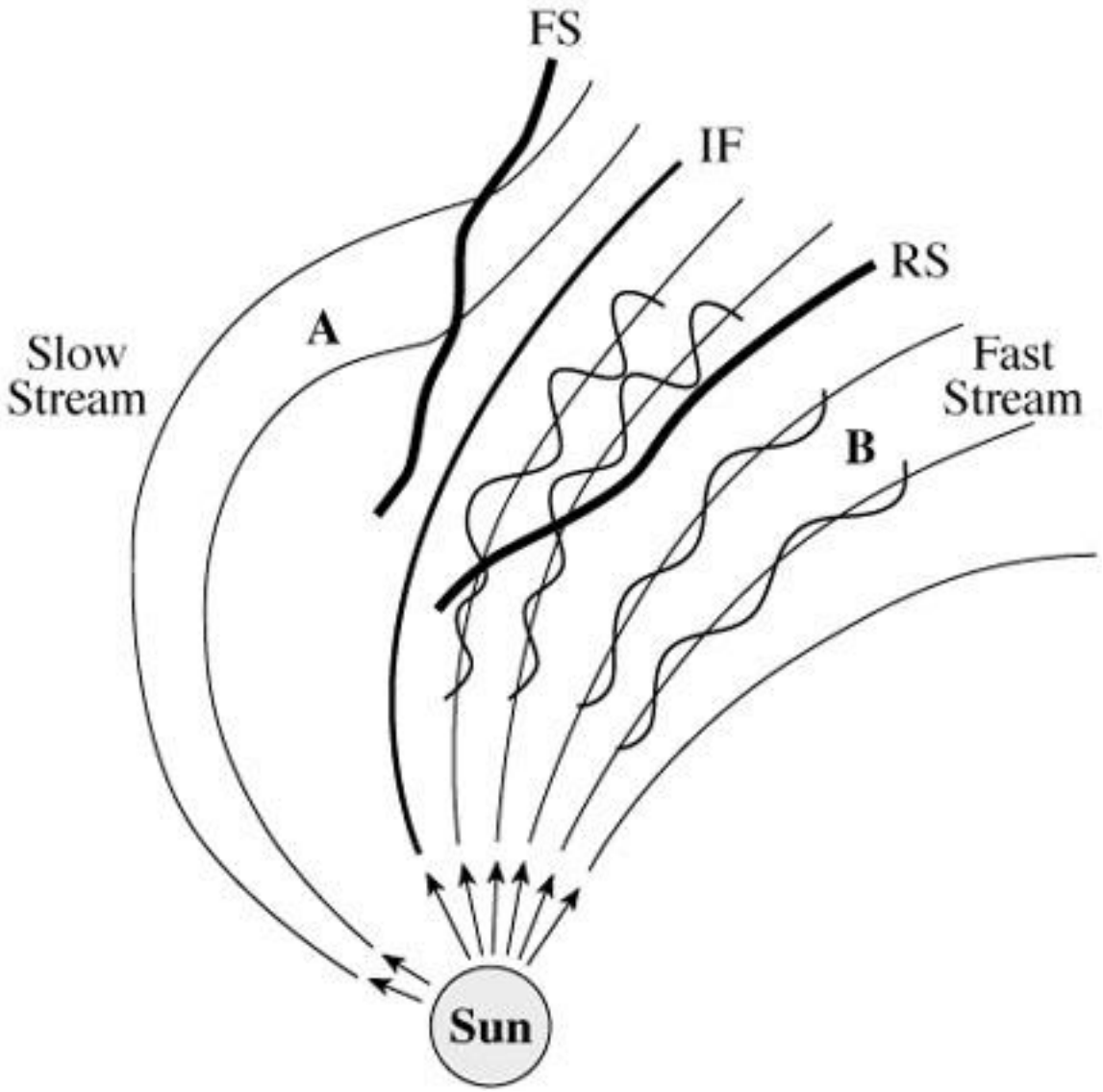
Slow speed

- from active regions;

solar equator

- high density

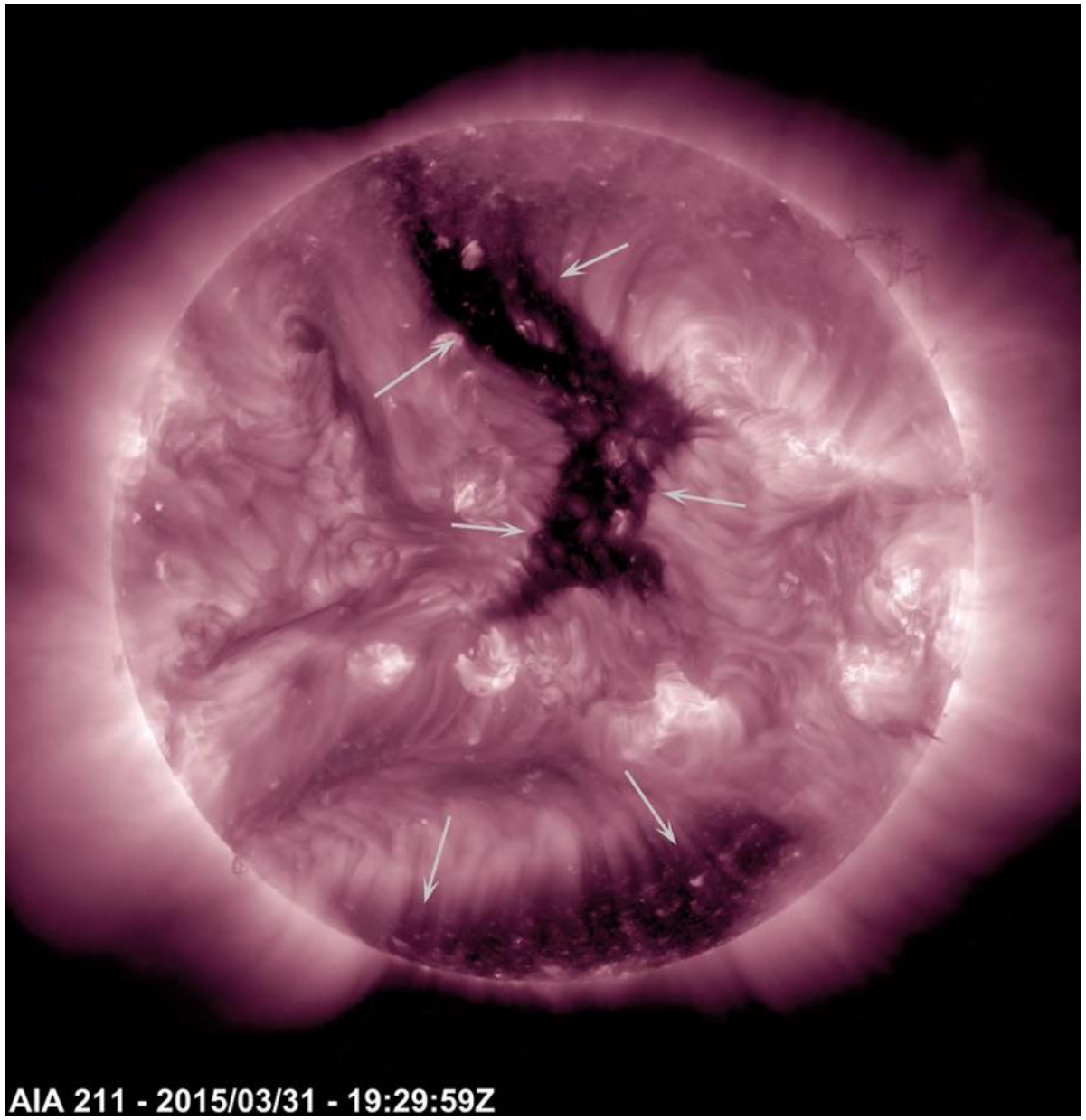
Space weather causes: co-rotating interacting regions

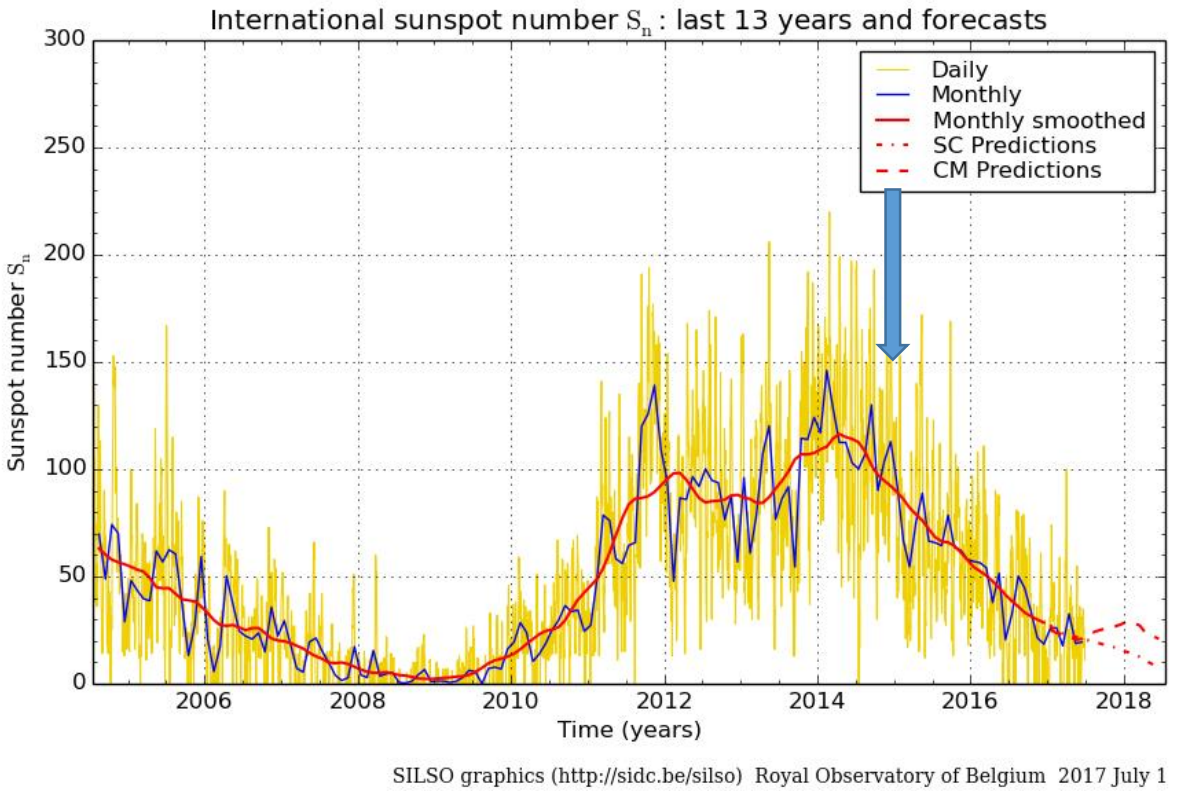


Kenneth R. Lang, Tufts University (2010)

- Formed due to the interaction between fast and slow solar-wind streams
- The magnetic fields of the slow/fast streams in the solar wind are more curved/radial due to the lower/higher speeds
- The Co-rotating Interaction Regions are bounded by a forward shock (FS) and a reverse shock (RS)
- Source for particle acceleration in the IP space

Space weather causes: coronal holes





27-day re-appearance of coronal holes – recurrent geomagnetic storms

NASA/SDO

Space weather causes: solar flares

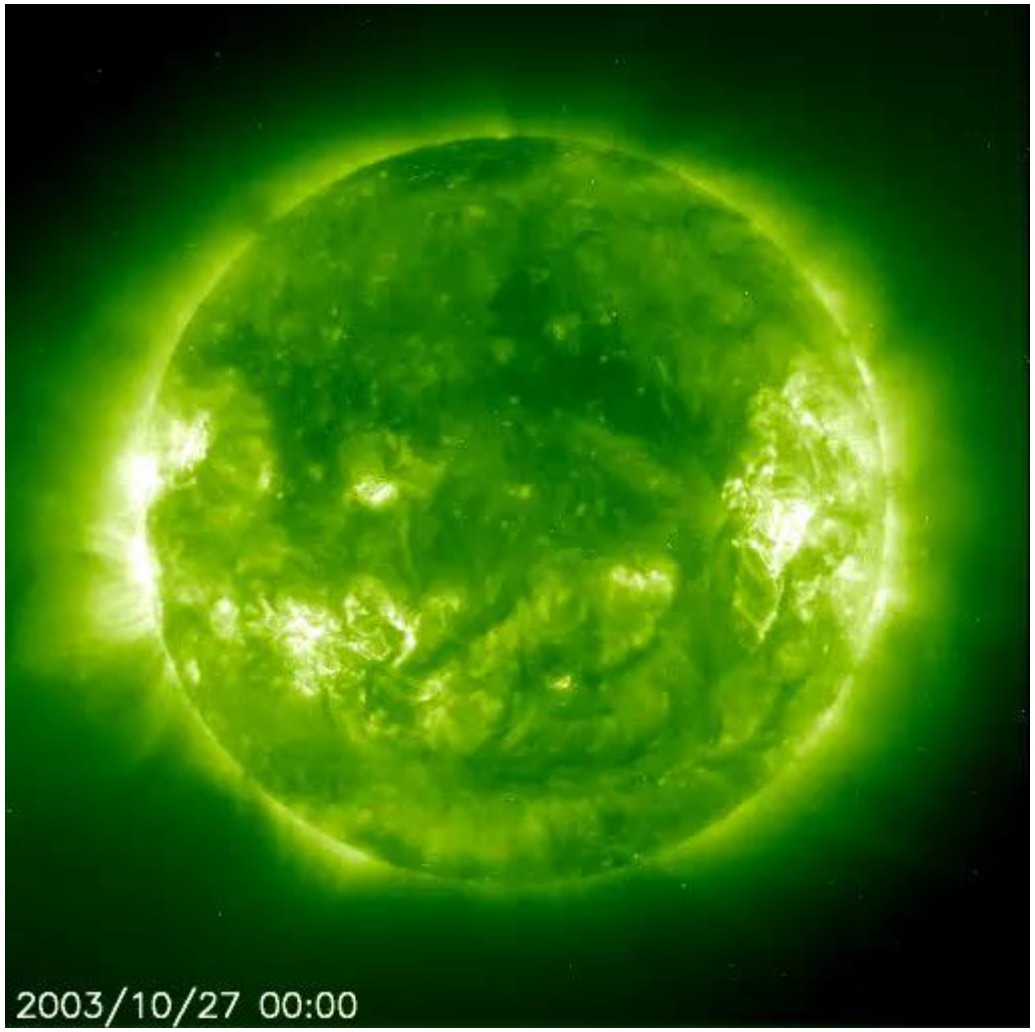
Sudden, rapid and intense variations of brightness: enormous explosions in the solar corona

- Radiation: from gamma to radio wavelengths (10^{32} erg or 10^{25} J)
- Mass motion
- Energetic particles

Occur near sunspot, over areas of different magnetic polarity

Space & ground-based observations

Forecasting efforts:
in development under FLARECAST.eu
(Horizon 2020 project)



Halloween storm events

ESA/NASA
SOHO/EIT 195 Å

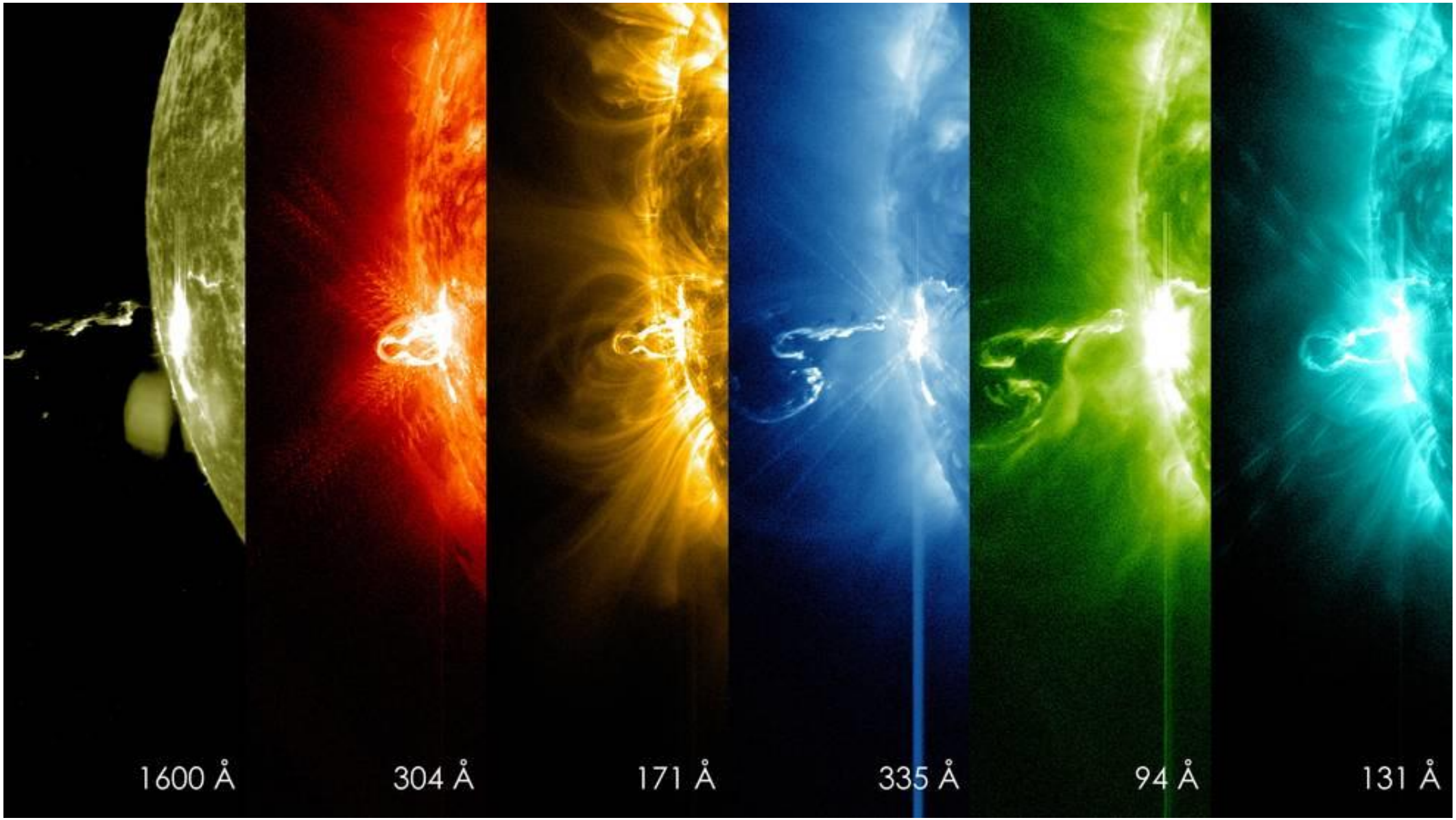
Space weather causes: solar flares

X4.9

S12E44

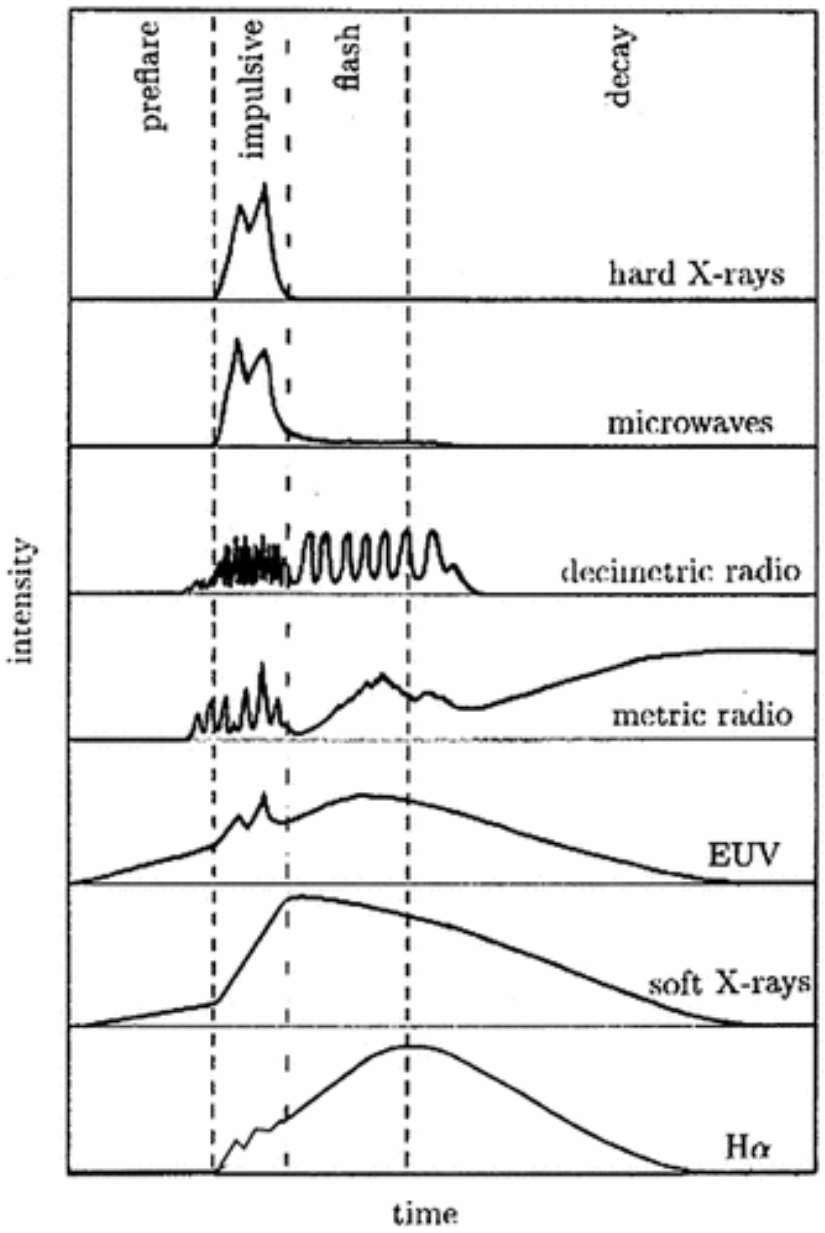
(X=10^{-4} W/m^2)

25-02-2014
(00:39 UT)

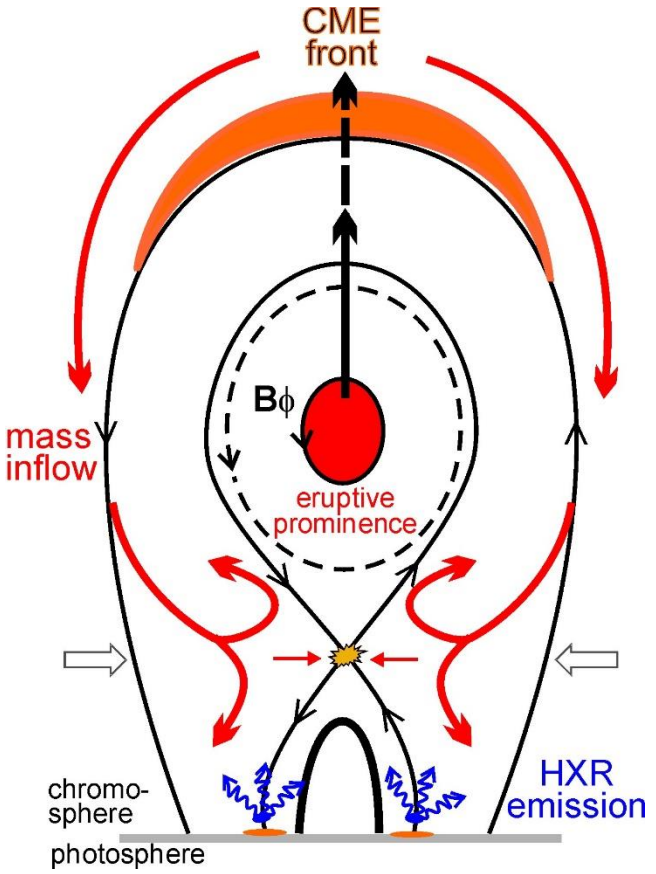


NASA SDO/AIA

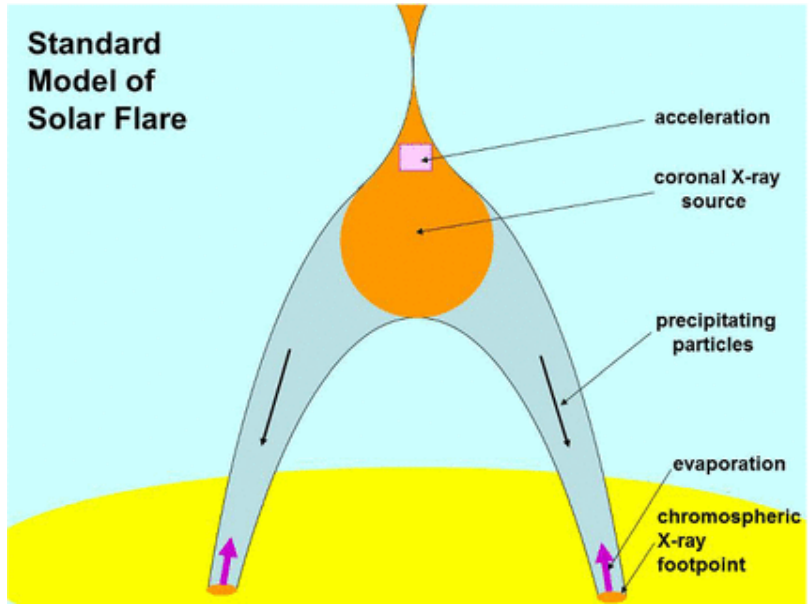
Space weather causes: solar flares



Benz (2002)



Temmer et al. (2008)



Benz (2016)

Due to build-up of magnetic energy in the solar atmosphere is suddenly released: process known as **magnetic reconnection**

Collection of cartoons:
http://solarmuri.ssl.berkeley.edu/~hhudson/cartoons/

Space weather causes: coronal mass ejections

Discovered in 1970s

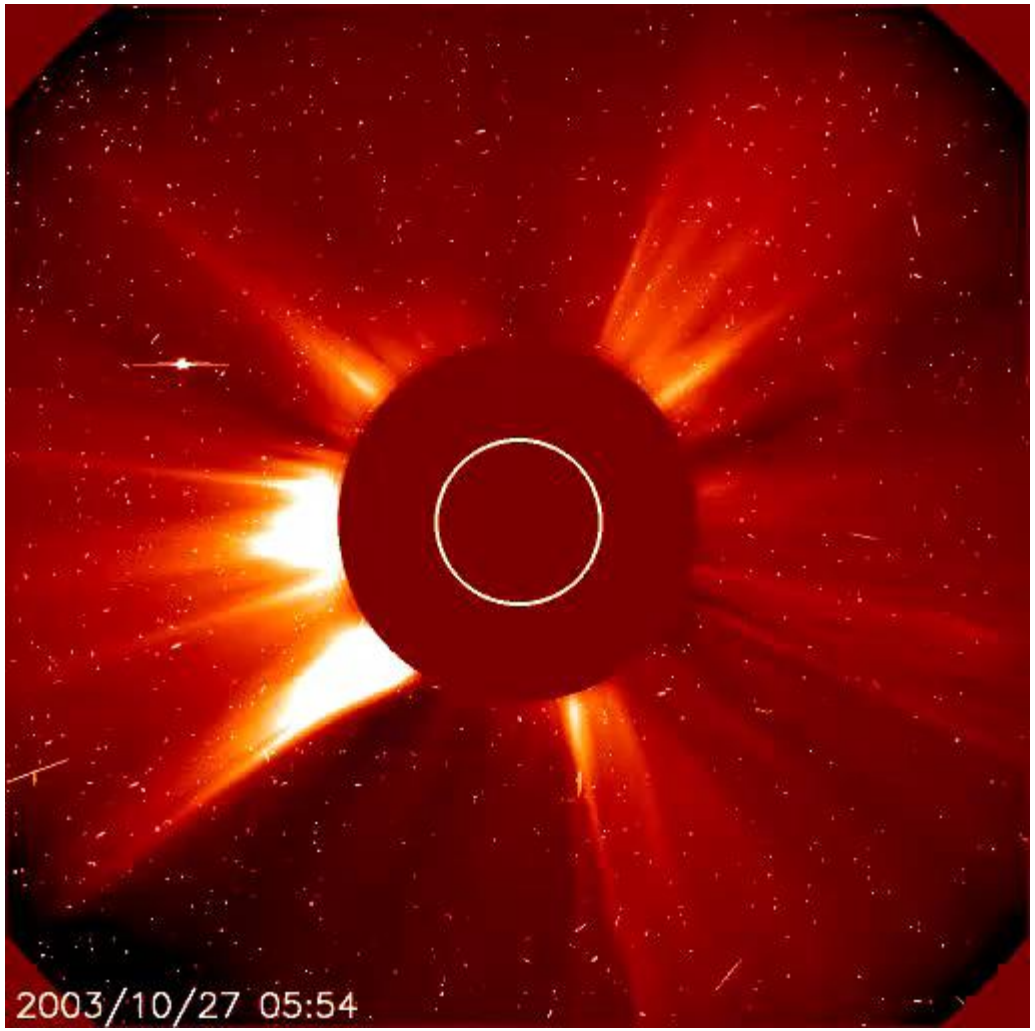
Observation type: occulted disk

Space & ground-based observations

Giant clouds of
plasma and magnetic field

Related to prominences

Speeds from 100s km/s to 3000 km/s



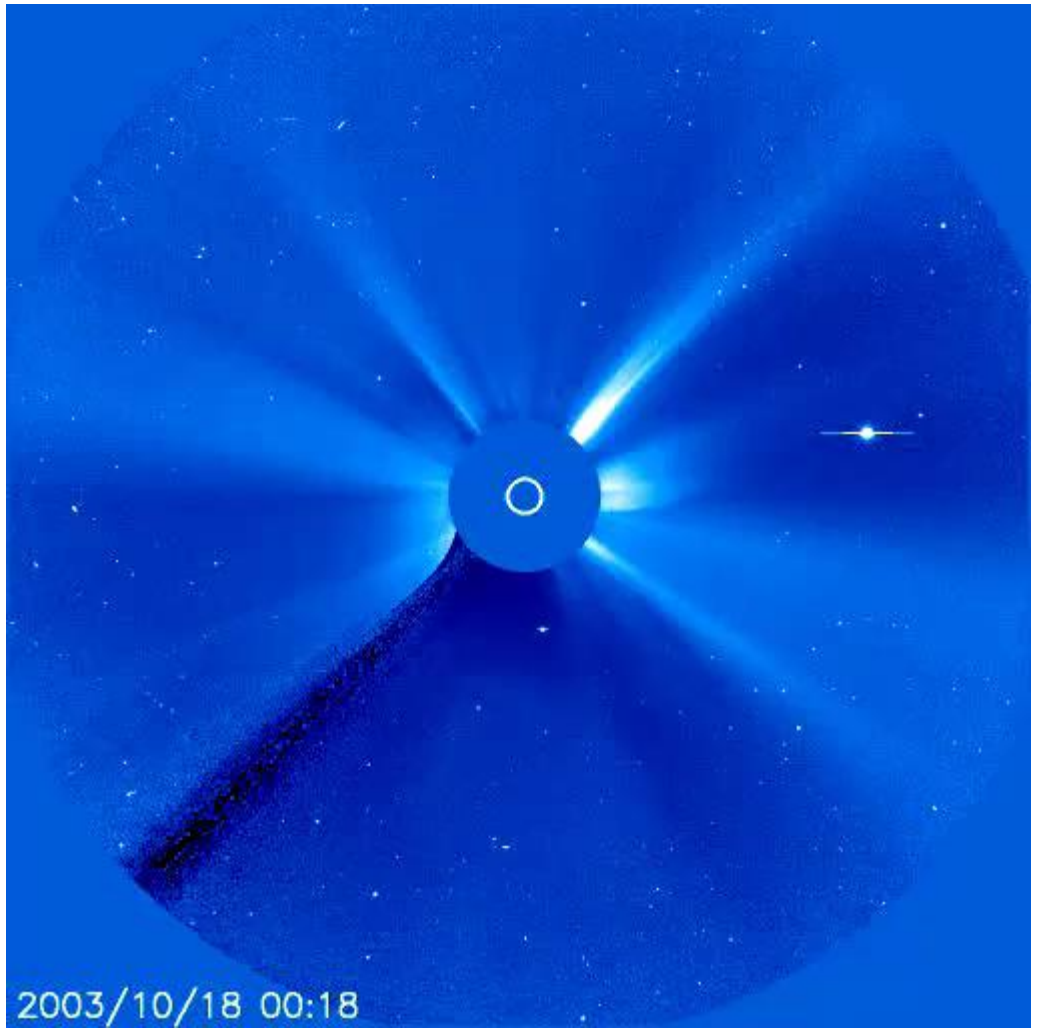
ESA/NASA
SOHO/LASCO C2
1.5 to 6 $R_\odot$

1 $R_\odot$ ≈ 700 000 km
≈1 arcsec

Space weather causes: coronal mass ejections

Main problem:

on-sky projected speed

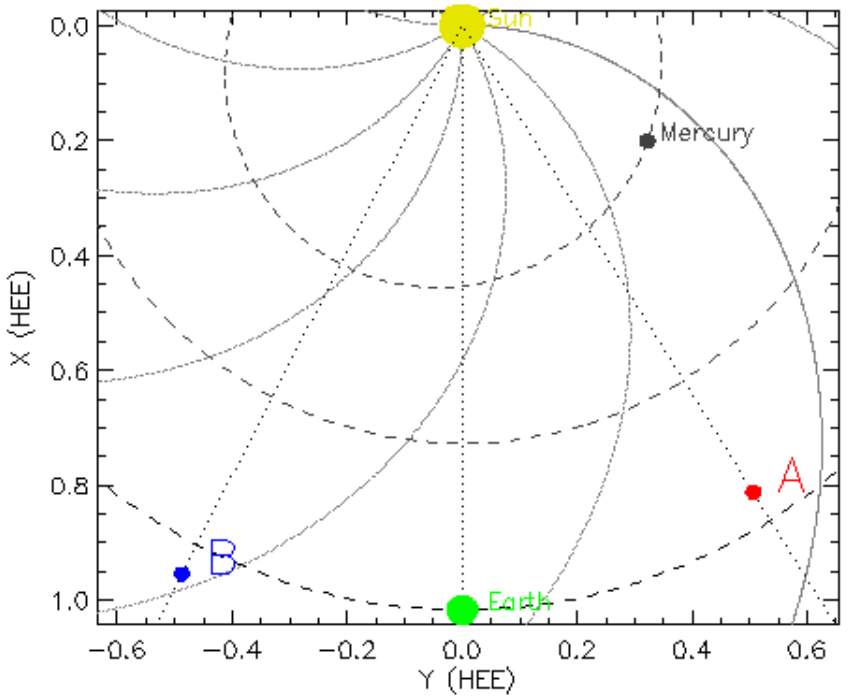


ESA/NASA
SOHO/LASCO C3
3.5 to 30 $R_\odot$

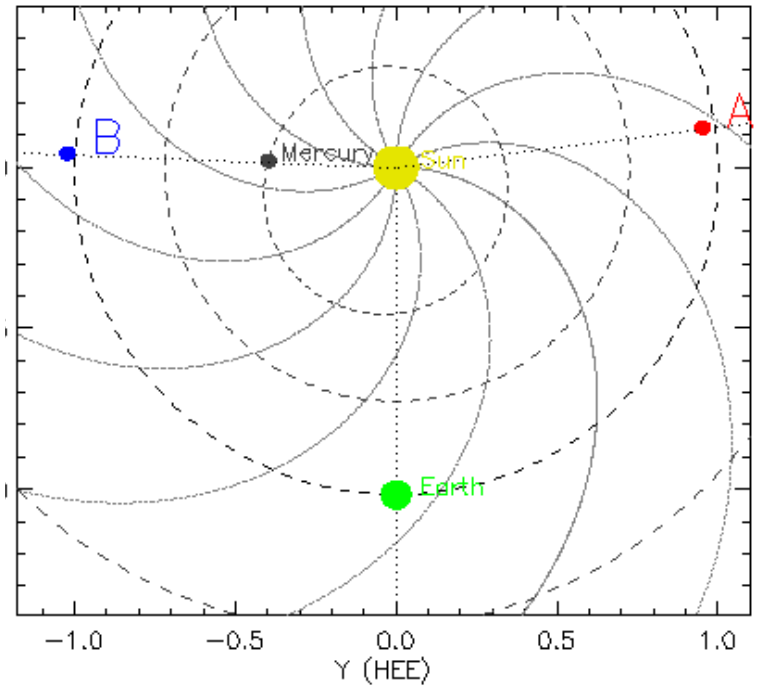
1 $R_\odot$ ≈ 700 000 km
≈1 arcsec

Space weather causes: coronal mass ejections

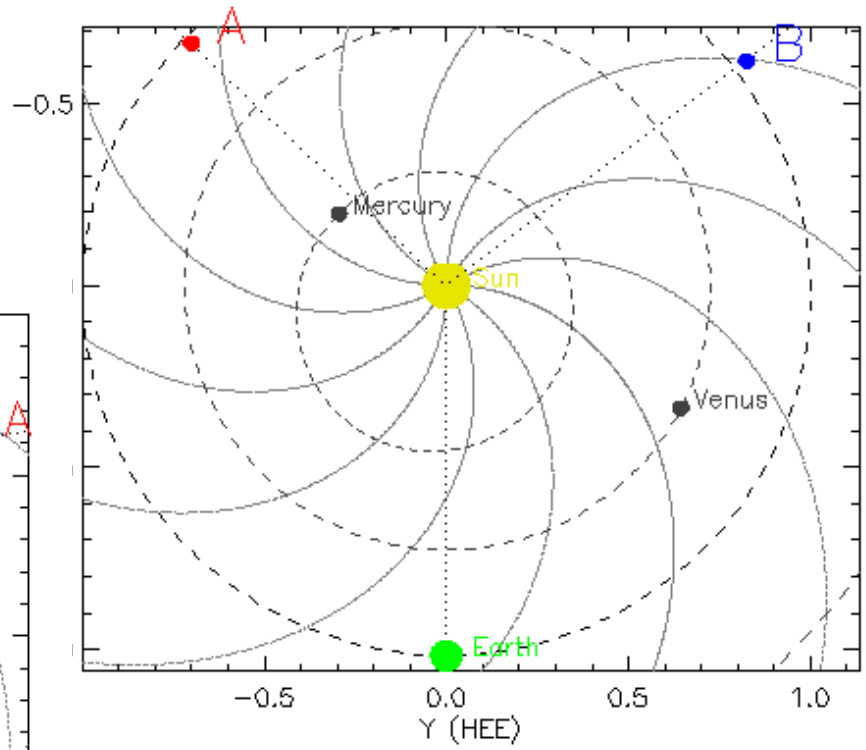
NASA/STEREO



2008



2011

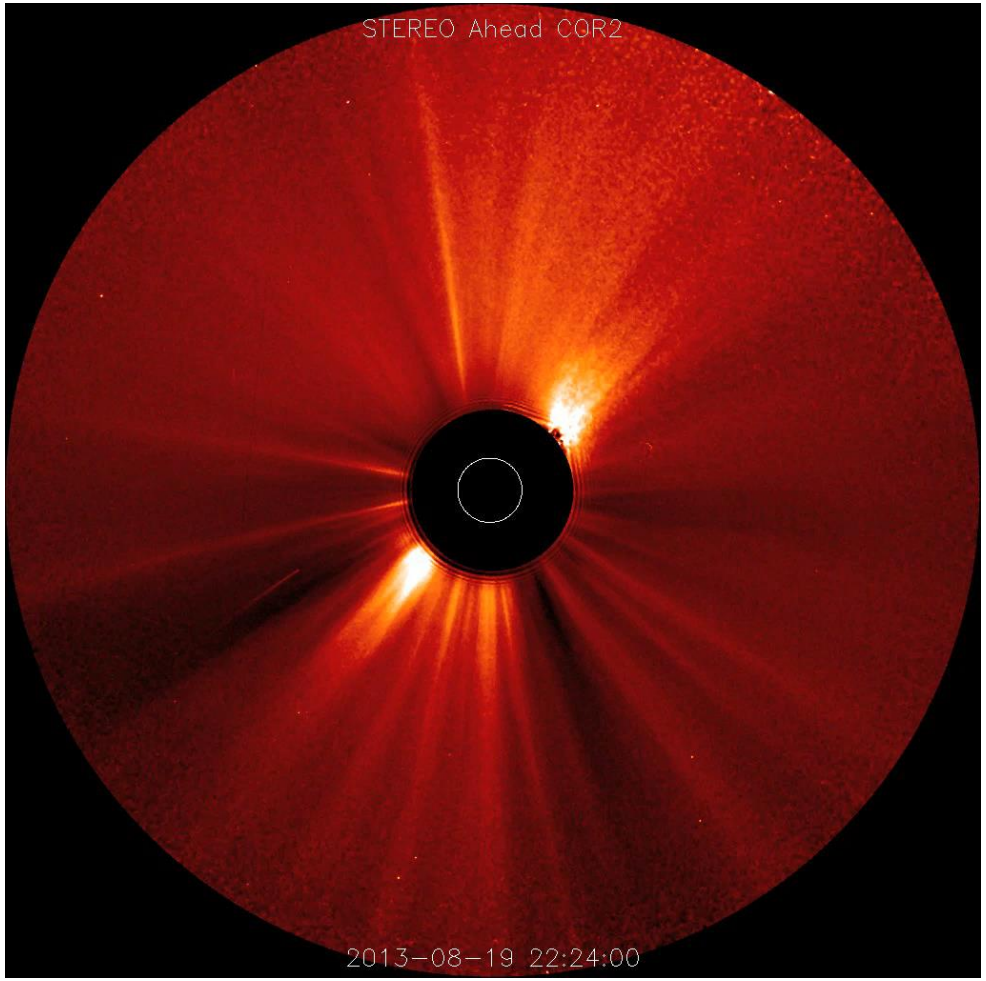


2017

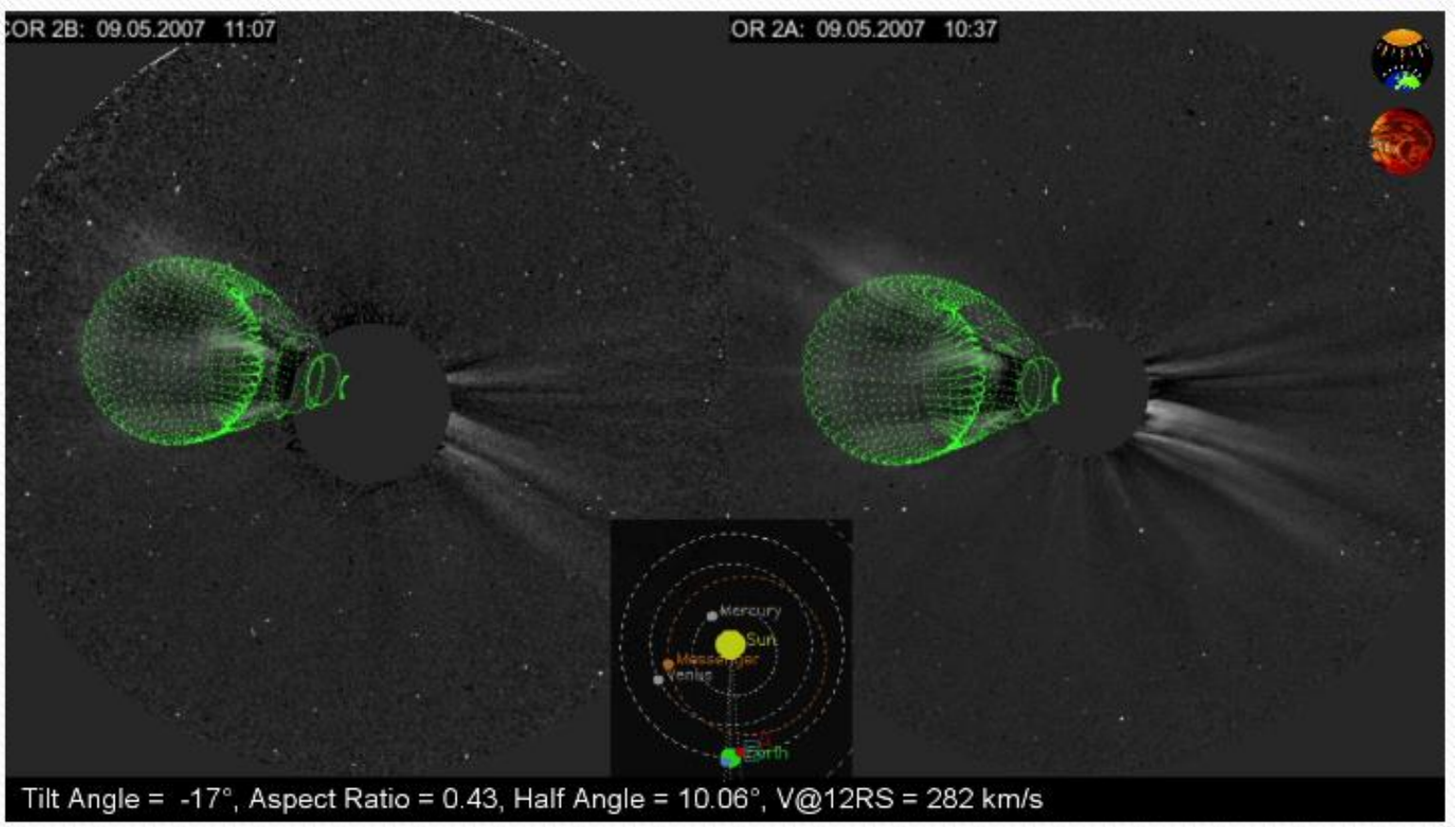
ST-B is blind since 09-2016!

https://stereo-ssc.nascom.nasa.gov

De-projection of the CME speed



Geometrical methods
Assumptions
Different models



Forecasting efforts – in development!

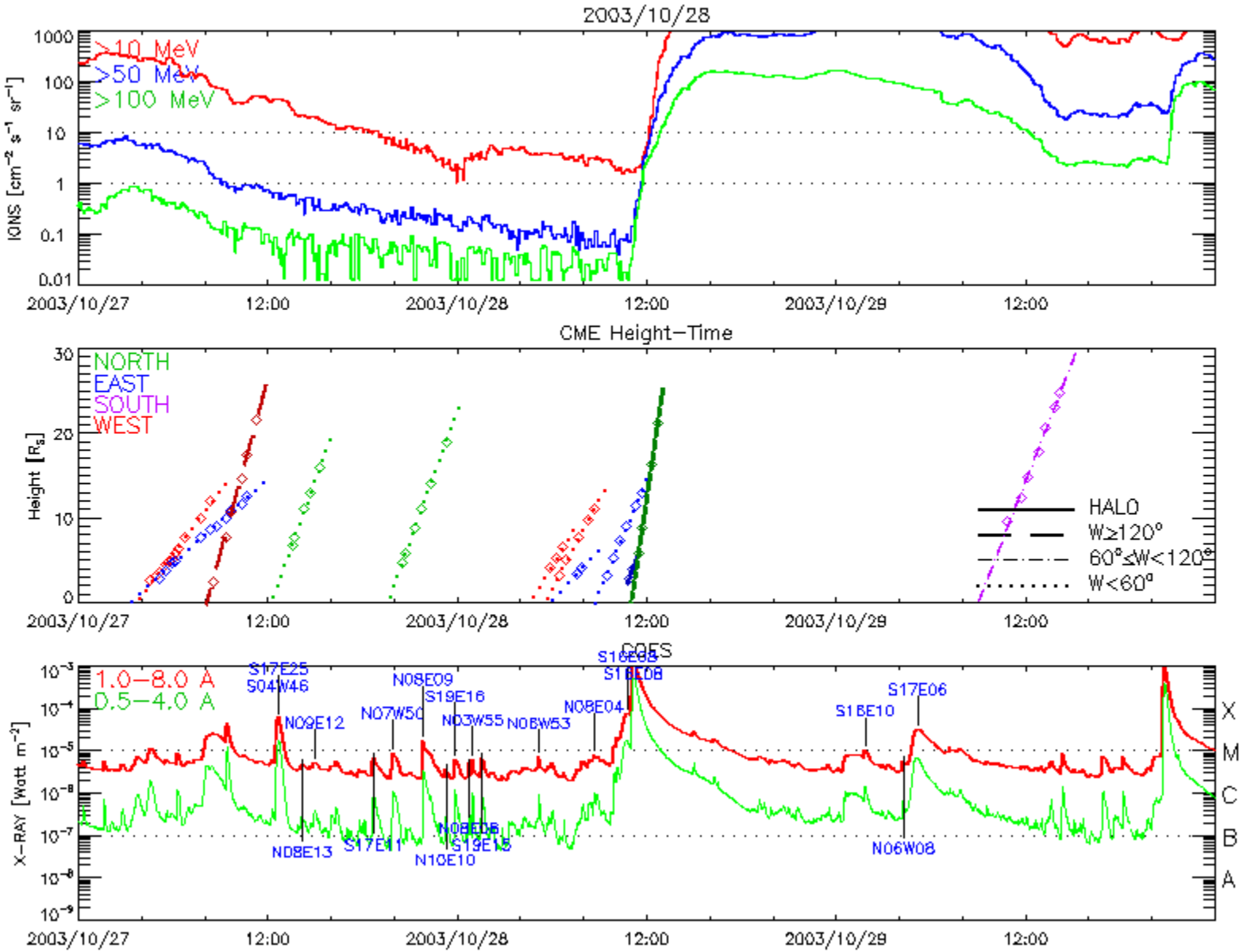
http://www.affects-fp7.eu/
https://www.helcats-fp7.eu/

Space weather causes: solar energetic particles

- electron, proton and ion enhancements
- from keV up to few GeV

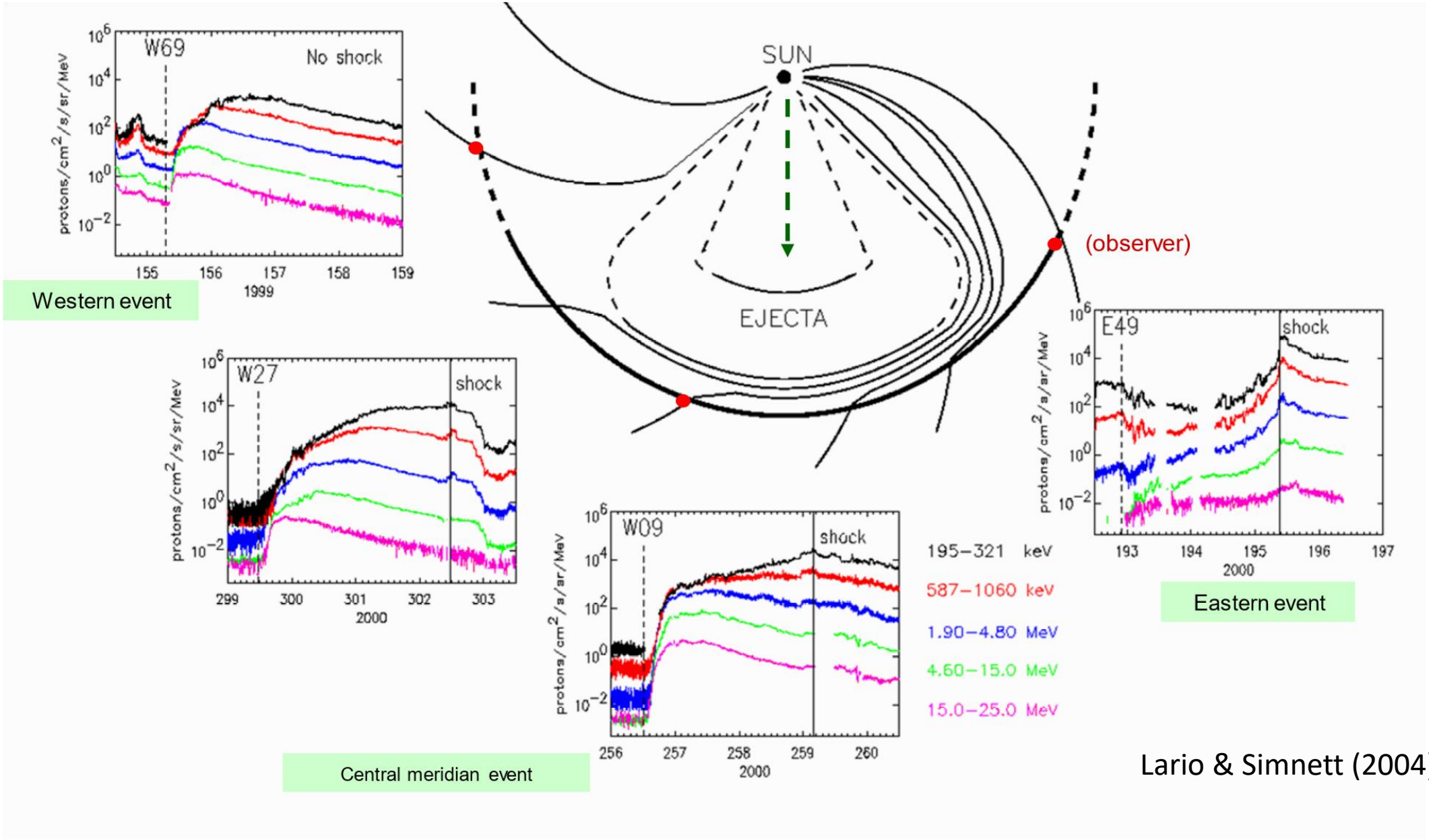
(travel time: 10s min to hours)

- follow in time solar activity
- velocity dispersion



https://cdaw.gsfc.nasa.gov/CME_list

Solar energetic particles: observations vs. origin location



Lario & Simnett (2004)

Solar energetic particles: the origin debate

Flares

- Magnetic reconnection (small scale)
- Escape from solar corona (stronger fields): open magnetic field lines

CMEs

- Shock acceleration (large-scale)
- Escape from high corona and IP space: open magnetic field lines

- Transport to satellite on magnetically connected IMF

“impulsive SEPs”

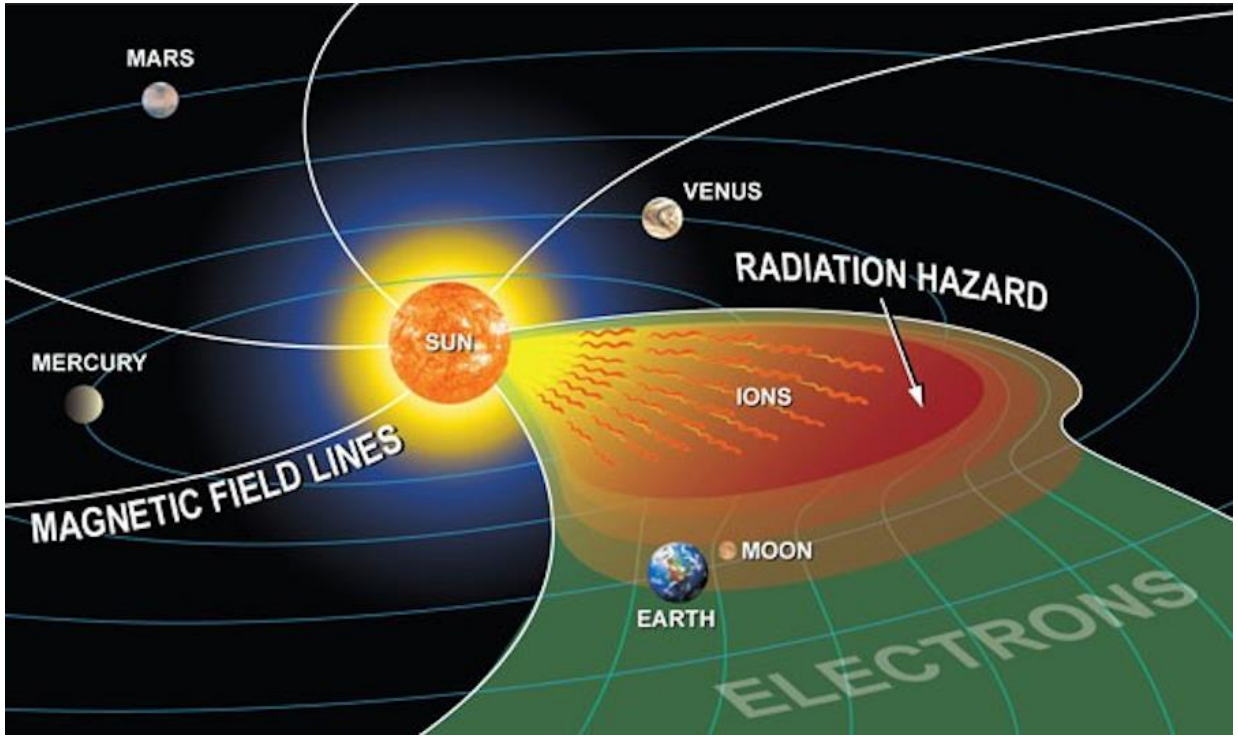
“gradual SEPs”

➢ Common properties (e.g. shock waves)

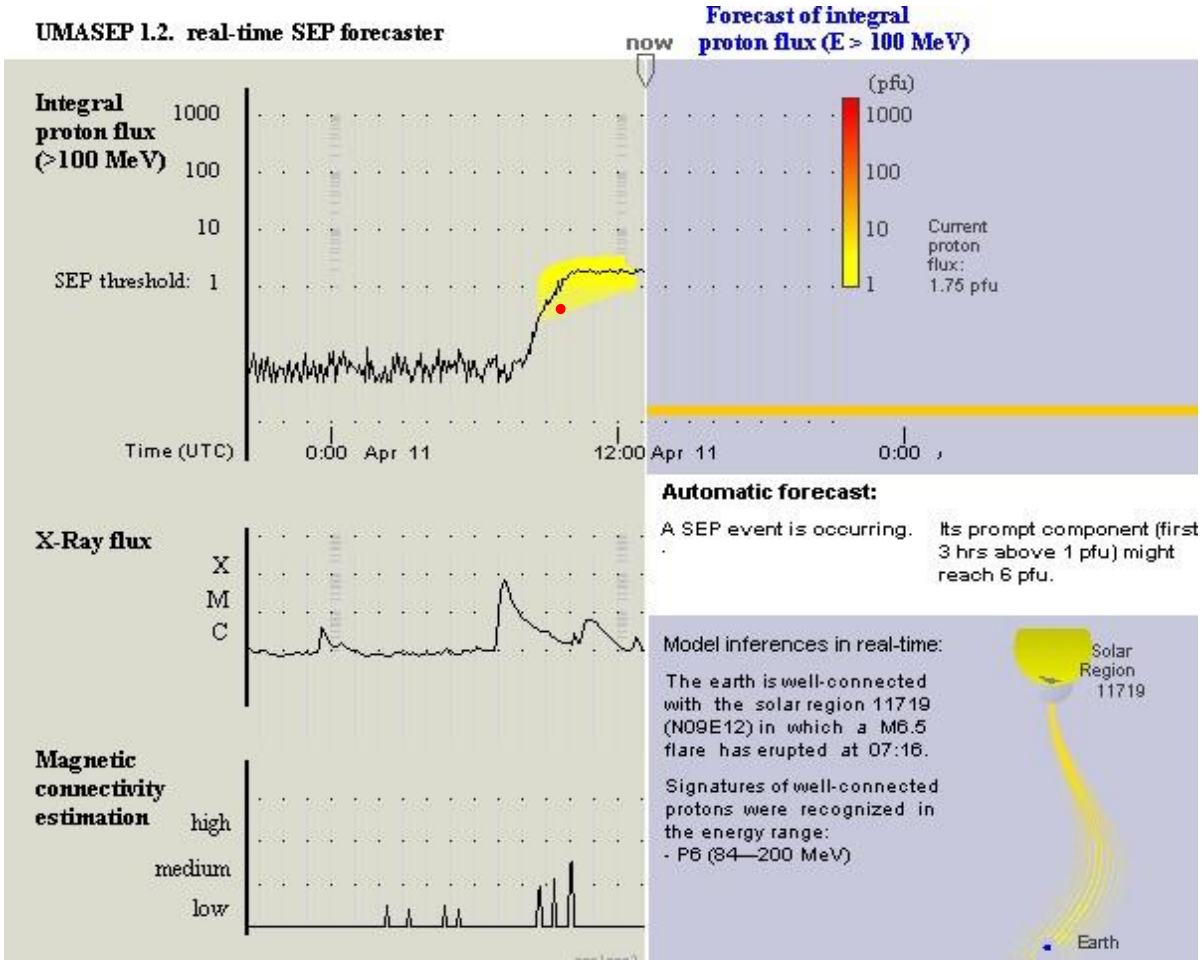
➢ Many intermediate cases

Solar energetic particles: forecasting efforts

2 examples



Posner (2009)



M. Nunez (2011, 2015)
http://spaceweather.uma.es/forecastpanel.htm

Forecast aim

- High probability of detection
- Low false alarm ratio
- Early warning time

Solar energetic particles: catalogs at SRTI-BAS

Catalogs of Solar Energetic Particles

© SRTI-BAS 2017 Last modified 05/18/2017 17:17:48

Wind/EPACT proton event catalog

SOHO/ERNE proton event catalog

Other particle catalogs

Supported by
Space Climate Group
Space Research and Technology Institute
Bulgarian Academy of Sciences

Contact: R. Miteva
Web-support: D. Danov

StatCounter "Number of Visits" from Jan. 12, 2017 until now is 000136

Wind/EPACT proton event catalog

Solar cycle 24: 2009-present

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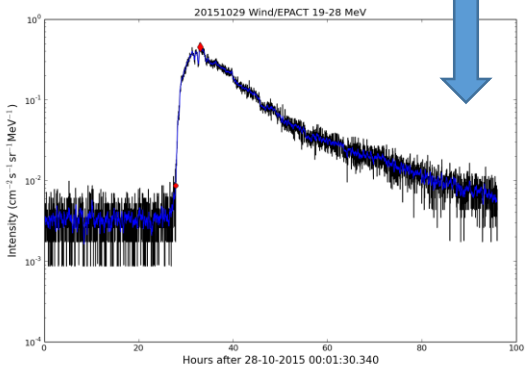
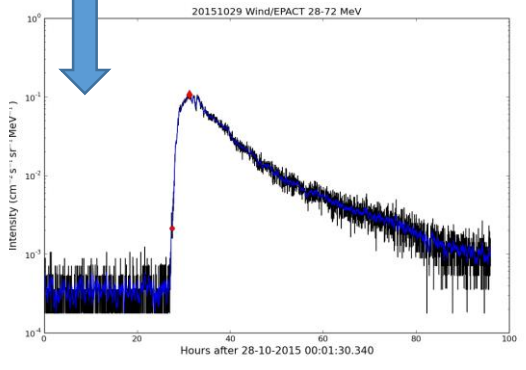
Back to list of Catalogs | Back to Wind/EPACT | Solar cycle 23: 1996-2008

Event date	19-28 MeV			28-72 MeV	Flare	CME	Comment
yyyy-mm-dd	onset time (UT)	peak time (UT)	J_p (cm^2 s sr MeV)$^{-1}$	J_p (cm^2 s sr MeV)$^{-1}$	SXR class/ onset time (UT)/ location	time (UT)/ speed (km s^{-1})/ width (deg)	
2009	-	-	-	-	-	-	no SEP events
2010-05-07/08	-	-	-	-	-	-	data gap
2010-05-12/18	-	-	-	-	-	-	data gaps
2010-06-12	04:04	08:39	0.0123	0.002	M2.0/00:30/N23W43	01:32/489/119	
2010-08-03	15:13	18:25	0.0478	0.0014	u	u	
2010-08-07	22:45	01:43nd	0.0111	0.0014	M1.0/17:55/N11E34	18:36/871/360	
2010-08-14	11:15	13:05	0.158	0.0184	C4.4/09:38/N17W52	10:12/1205/360	
2010-08-18	08:01	12:18	0.0486	0.0034	C4.5/04:45/N18W88	05:48/1471/184	
2010-09-09	03:02	04:25	0.0071	0.0007	C3.3/23:05^{pd}/N21W87	23:27^{pd}/818/147	
2010-12-07	-	-	-	-	-	-	data gap





http://newserver.stil.bas.bg/SEPcatalog

catalog release in late-2017

Solar energetic particles: new project on SEP origin

The origin of solar energetic particles: solar flares vs. coronal mass ejections

2-year project
bilateral cooperation between Bulgaria and Russia

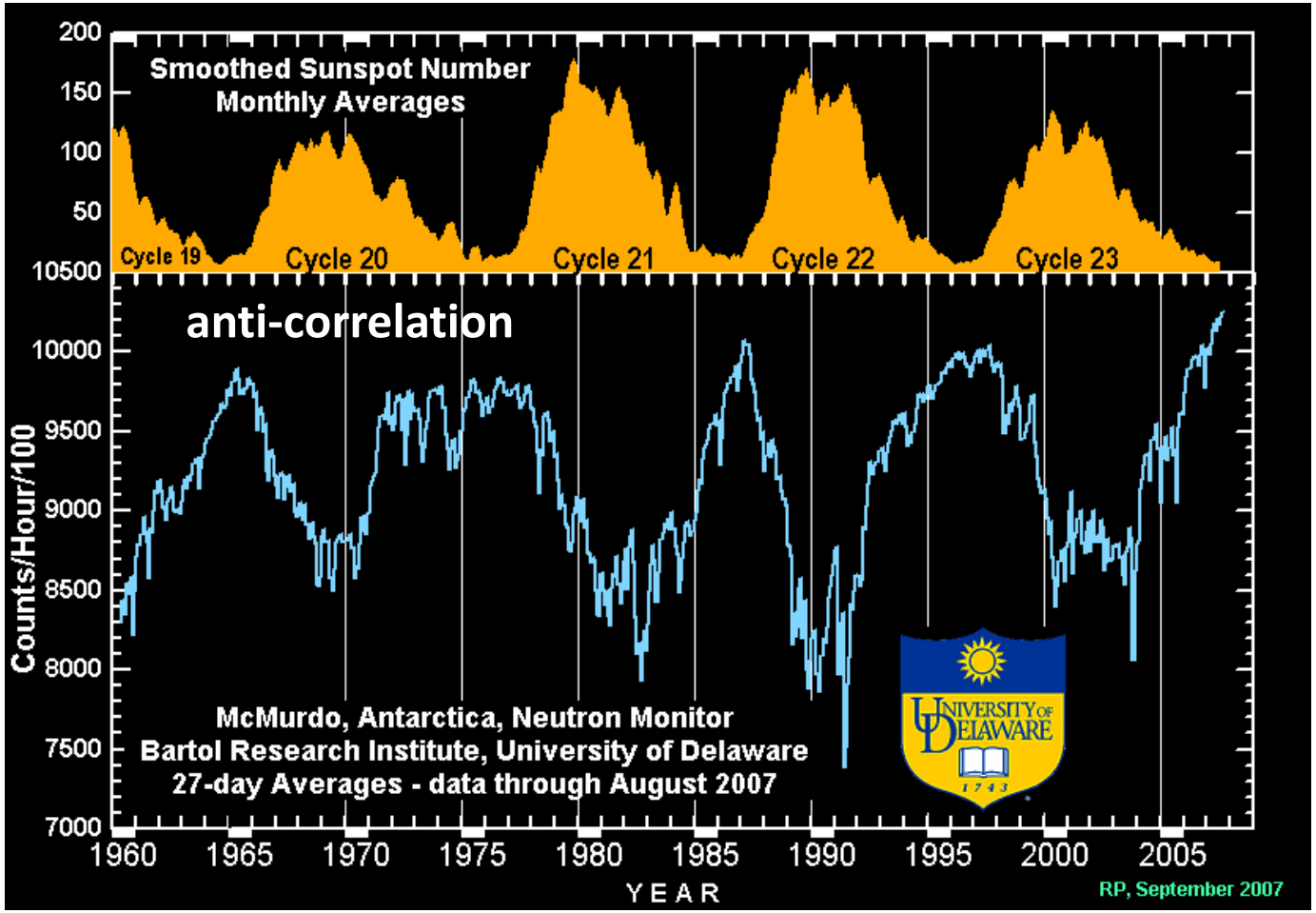
Bg-team
R. Miteva (coordinator)
N. Petrov
Ts. Tsvetkov
D. Danov

Ru-team
L. Kashapova (coordinator)
I. Myagkova
A. Bogomolov
N. Meshalkina
I. Myshyakov
D. Zhdanov

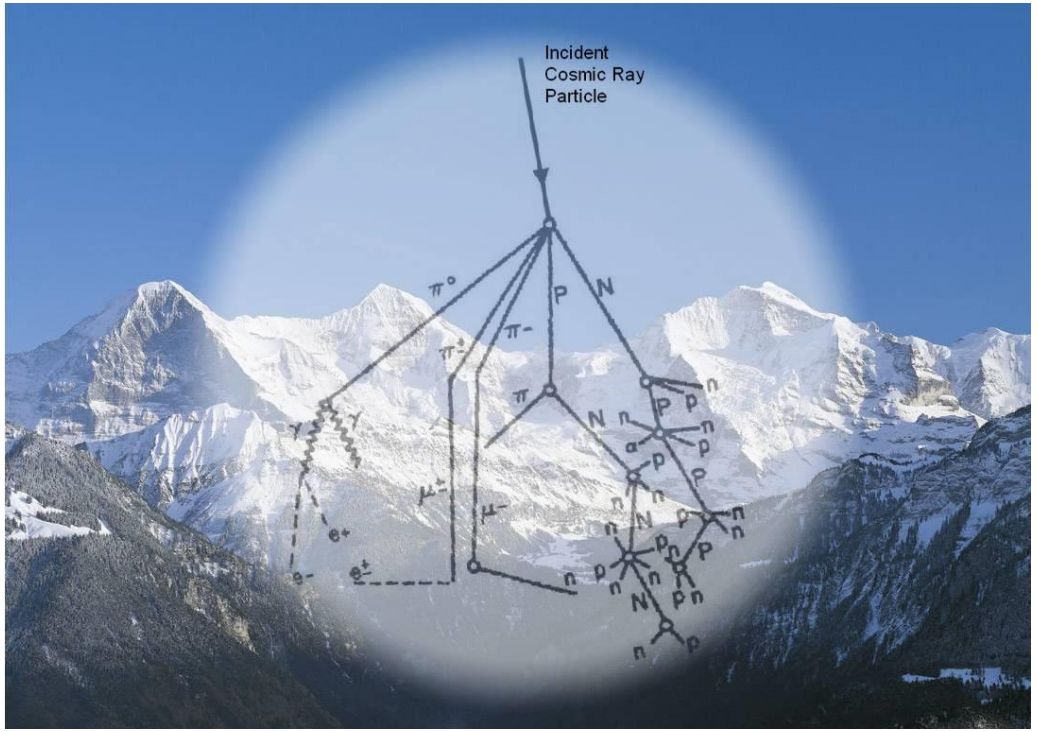
ФОНД НАУЧНИ ИЗСЛЕДВАНИЯ
МИНИСТЕРСТВО НА ОБРАЗОВАНИЕТО И НАУКАТА

Funded by the National Science Fund No. ДНТС/Russia 23-Jun-2017
www.fni.bg

Solar energetic particles vs. galactic cosmic rays



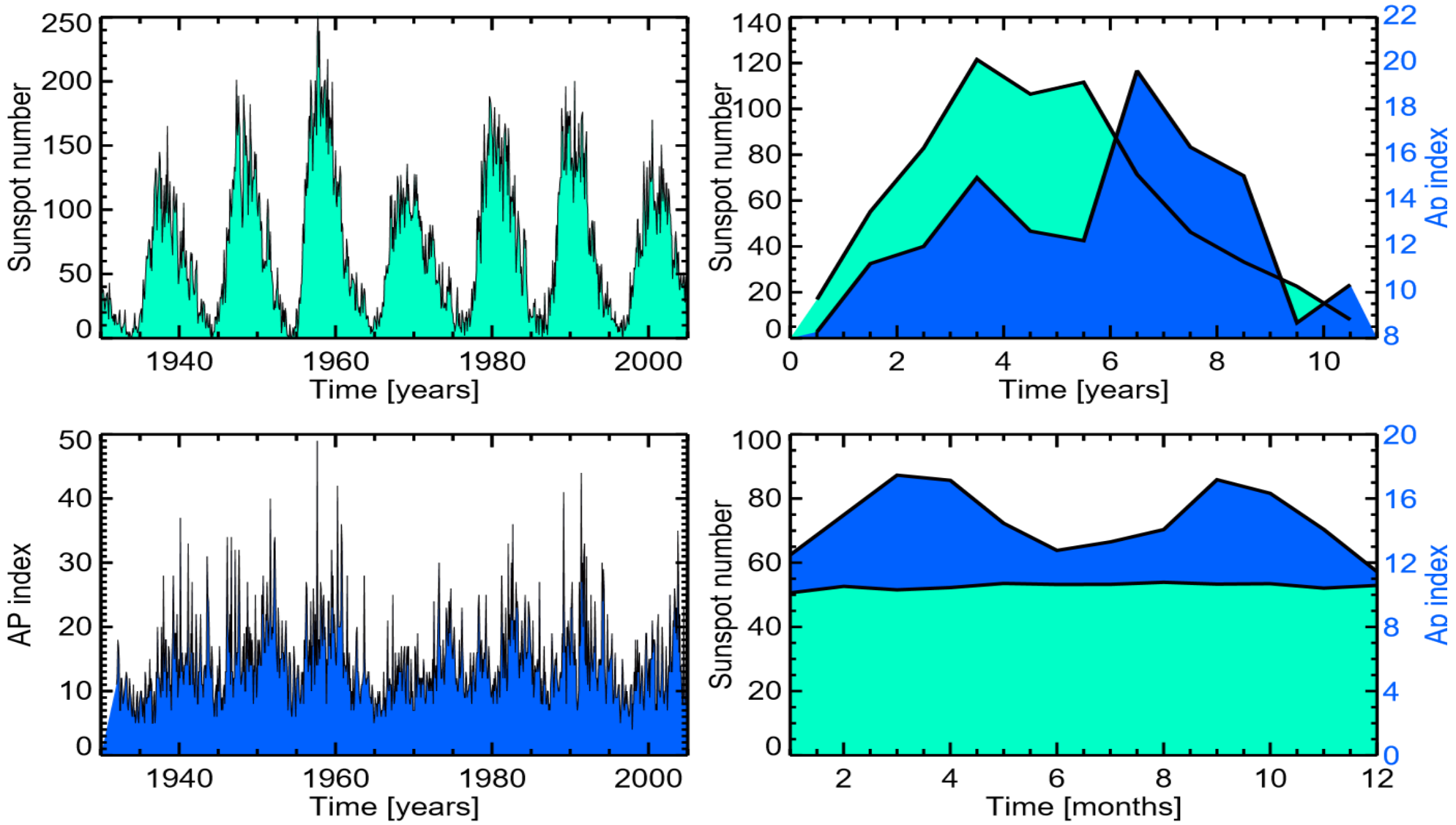
http://neutronm.bartol.udel.edu/catch/cr3.html



http://www.nmdb.eu/

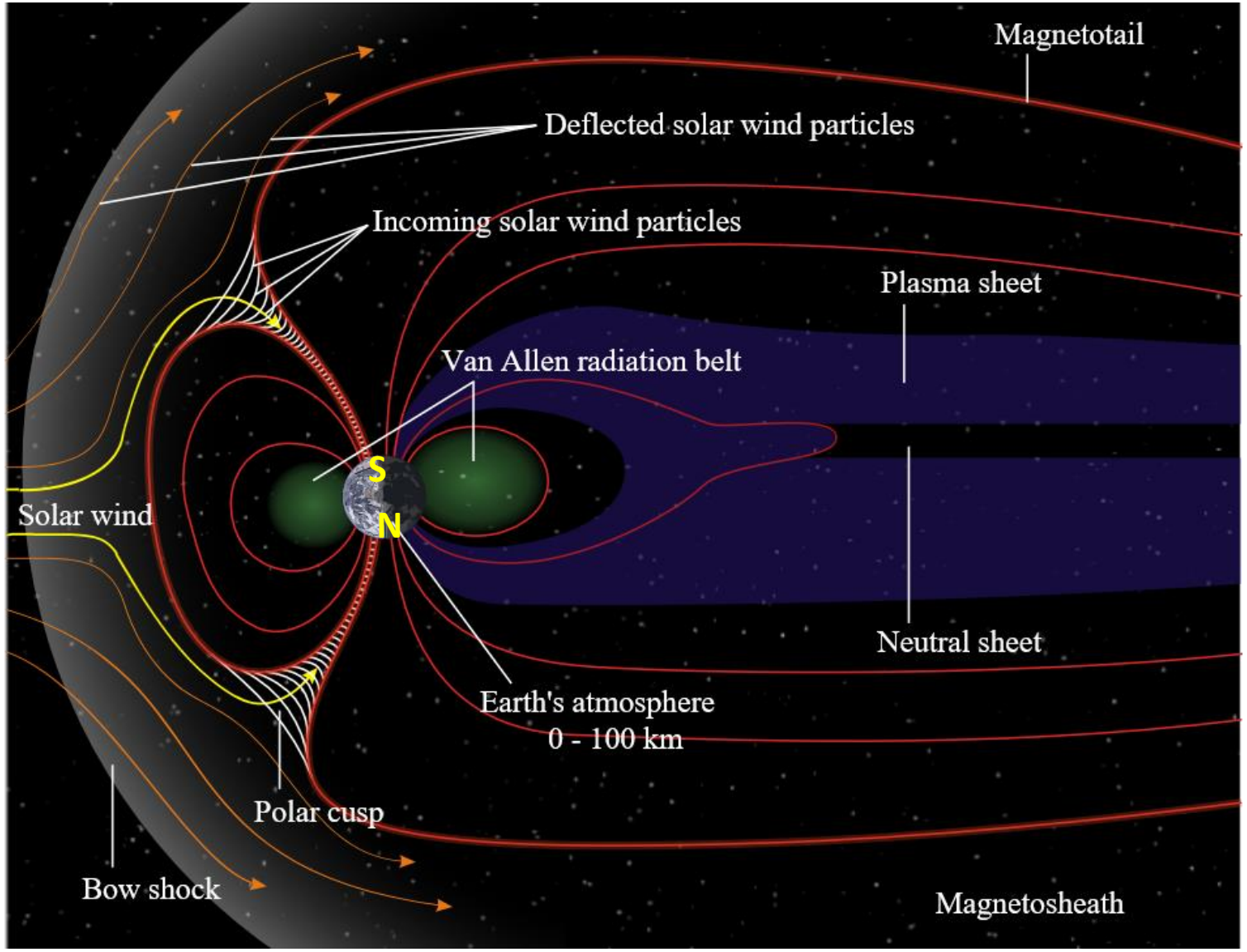
Solar energetic particles vs. geomagnetic activity

correlation



Pulkkinen (2007)

Space weather causes: terrestrial magnetosphere



Geomagnetic storms (and sub-storms)
South component of IMF
Fast speed of incoming plasma

Measurements
Component of Earth's magnetic field

~60 μT=0.6 Gauss in the polar regions
~30 μT=0.3 Gauss at the equator
1 Tesla = 10^4 Gauss
11° tilt to rotational axis

https://en.wikipedia.org/wiki/Magnetosphere

Space weather causes: geomagnetic storms & sub-storms

Temporary disturbance of the Earth magnetic field

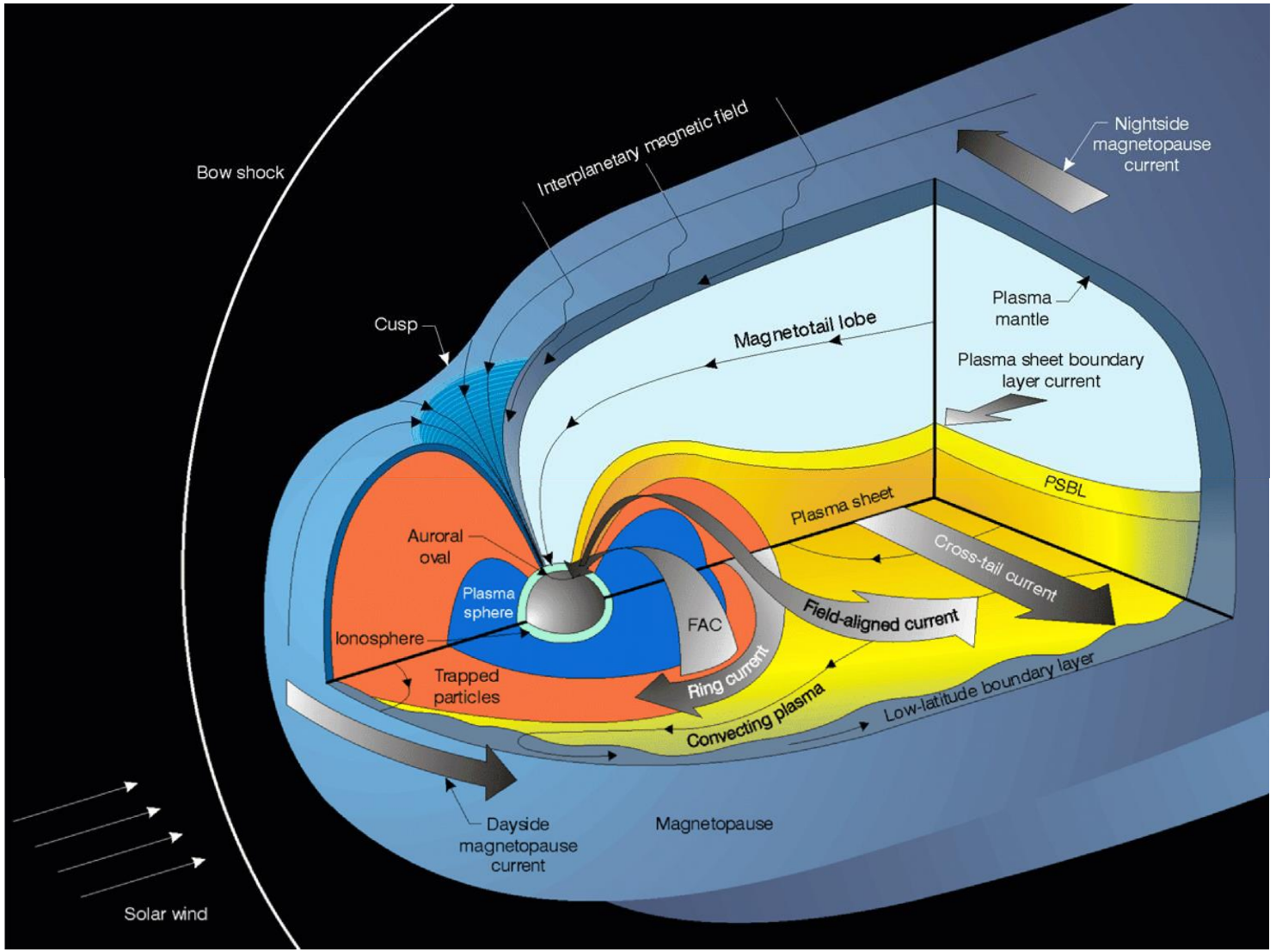
Due to

- CMEs (during solar max) – earliest after 18 hr (up to 3 days)
- and high speed solar wind streams (solar min): CIRs, coronal holes

Initial compression of the magnetosphere – induced currents – surface magnetic field drop

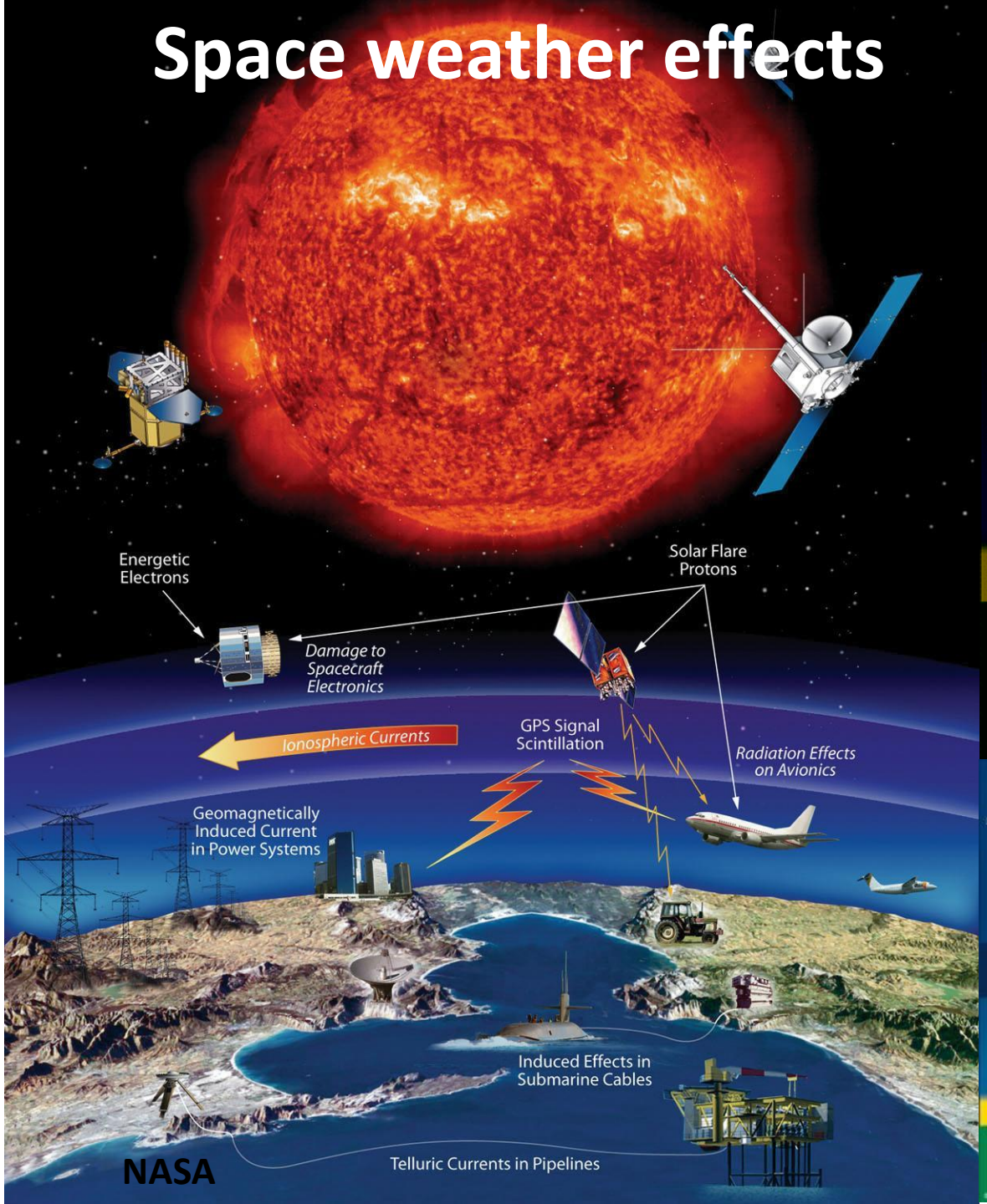
Reconnection; energy transfer; SEPs enter at the poles

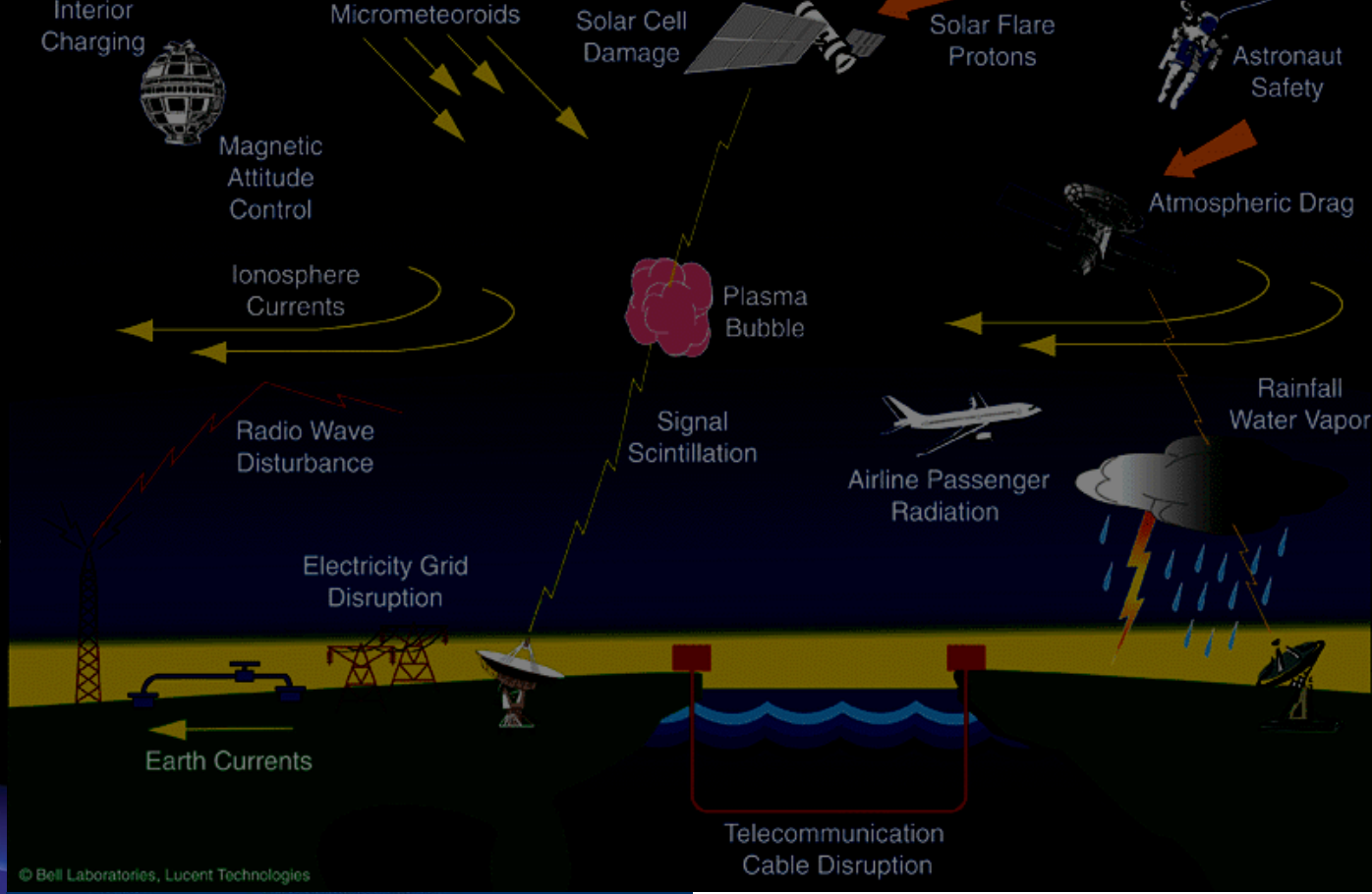
Planetary vs. aurora oval occurrence

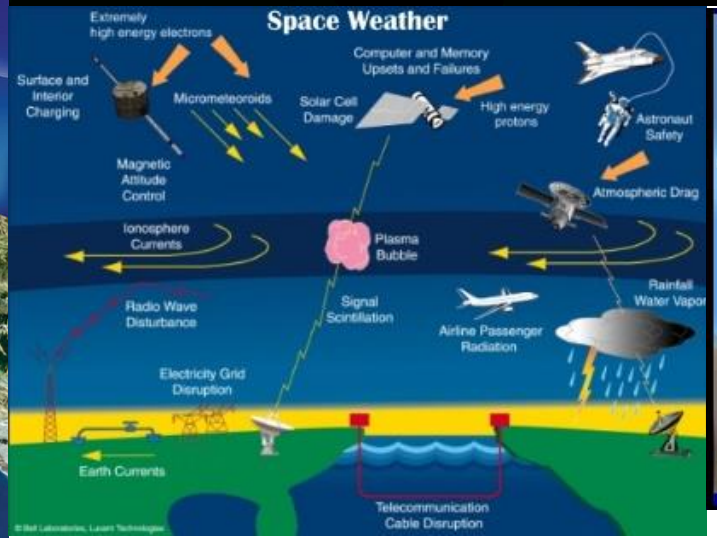


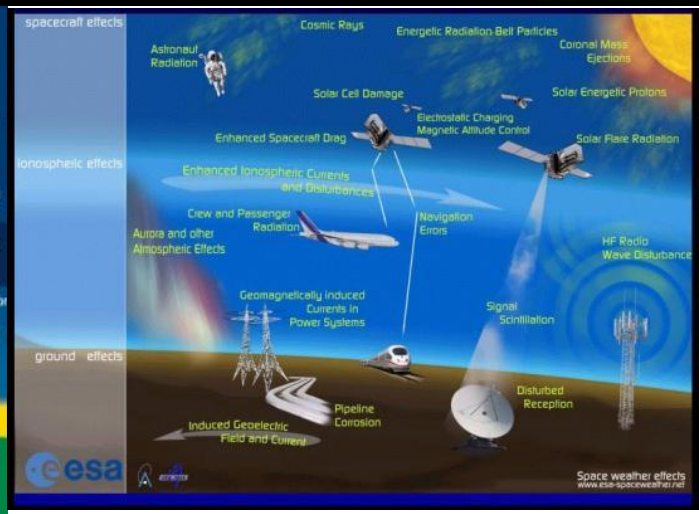
from presentation by F. Toffoletto, Rice University

Space weather effects









Space weather effects: solar flares

release flashes of radiation covering an immense wavelength range (from radio waves to Gamma-rays) that can:

- Lα 121.6 nm emission heats up the terrestrial atmosphere within minutes and cause **satellites to drop into lower orbits**

- **disturbance of radio signals**

Space weather effects: coronal mass ejections

ejected into interplanetary space as gigantic clouds of ionized gas, that after a few hours or days may eventually hit the Earth and cause, among other effects

- cause geomagnetic storms

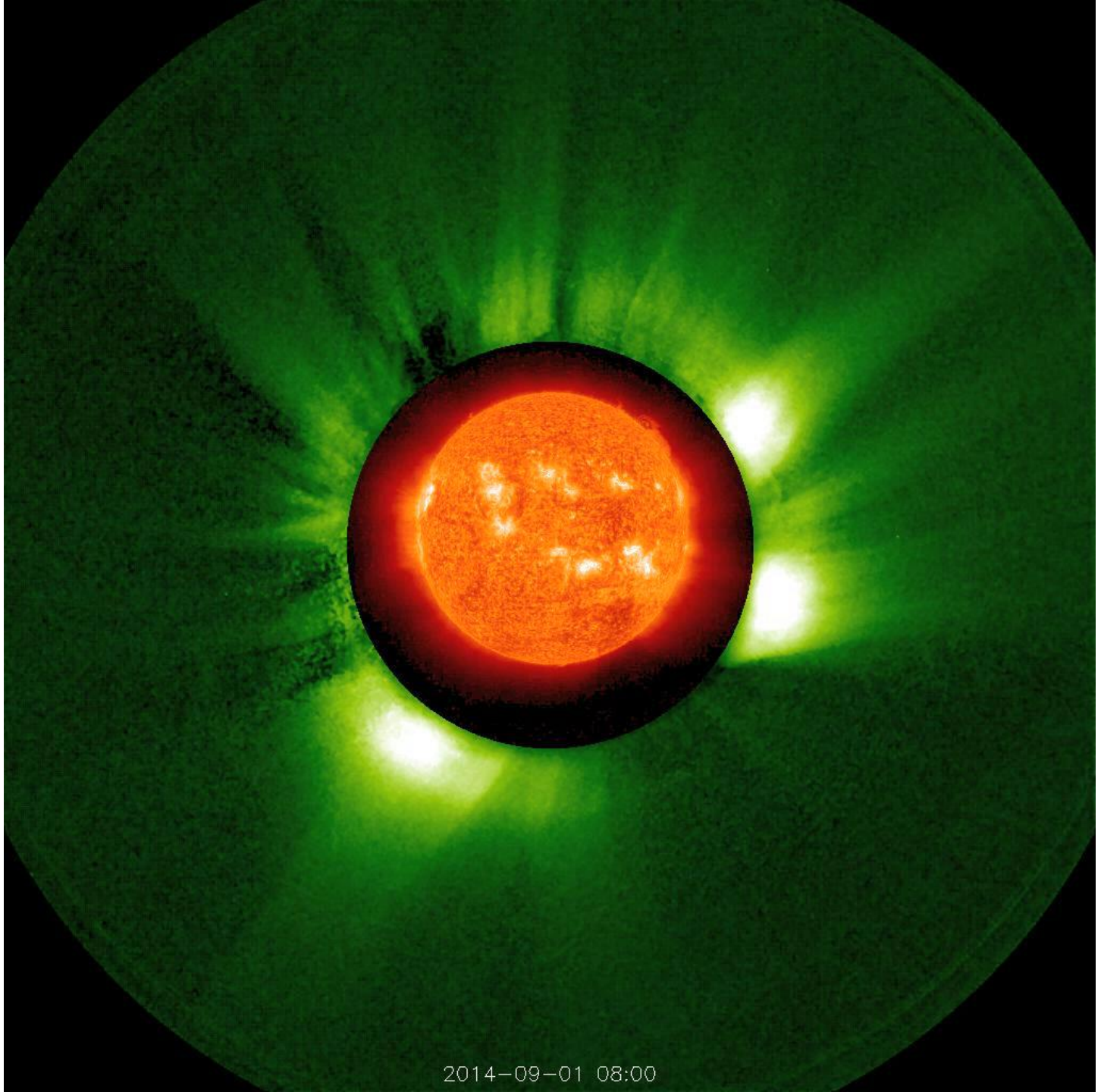
Space weather effects: solar energetic particles

accelerated to near-relativistic energies during major solar storms arrive at the Earth's orbit within minutes and may, among other things,

- Protons: severely endanger astronauts traveling through interplanetary space, i.e., outside the Earth's protective magnetosphere.

- Electrons: risk for satellites (instruments on board)

SEPs and
Satellite stability



NASA/SDO&STEREO

Mission to Mars

(or elsewhere outside the terrestrial magnetosphere)

Among the top health hazards for humans are:

(3) prolonged weightlessness, already known to weaken bones, muscles and vision

→ **possible solutions (e.g., ISS)**

(2) extreme isolation, which could lead to psychological problems

→ **possible solutions**

(1) space radiation that could cause cancer, central nervous system damage, cataracts or infertility

→ **NO solution yet!**

NASA Report No. IG-16-003
'NASA's efforts to manage health and human performance risks for space exploration'

Mission to Mars

(Bulgarian contribution)

Lessons learned from MIR & ISS stations

On route to and in Martian orbit

Space weather: internal planets in solar system

Mercury

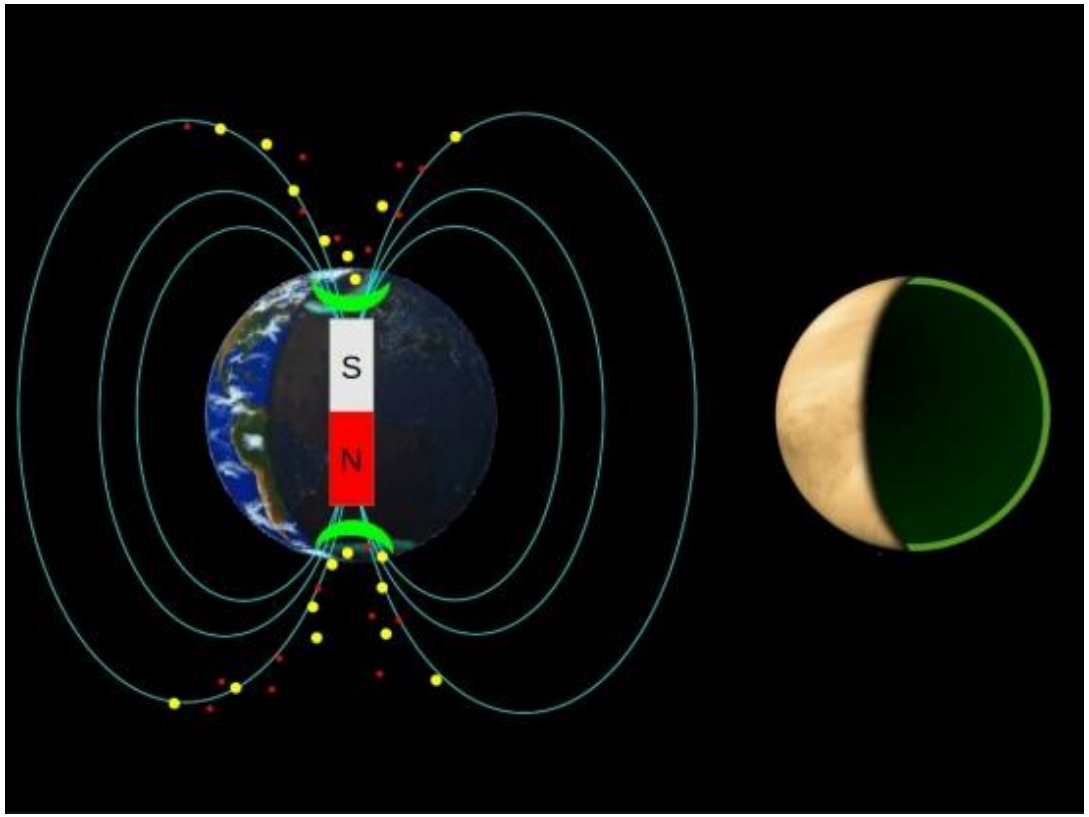
- exosphere (surface evaporation due to solar radiation)
- magnetic field (1 % from Earth's)

NASA/Messenger mission

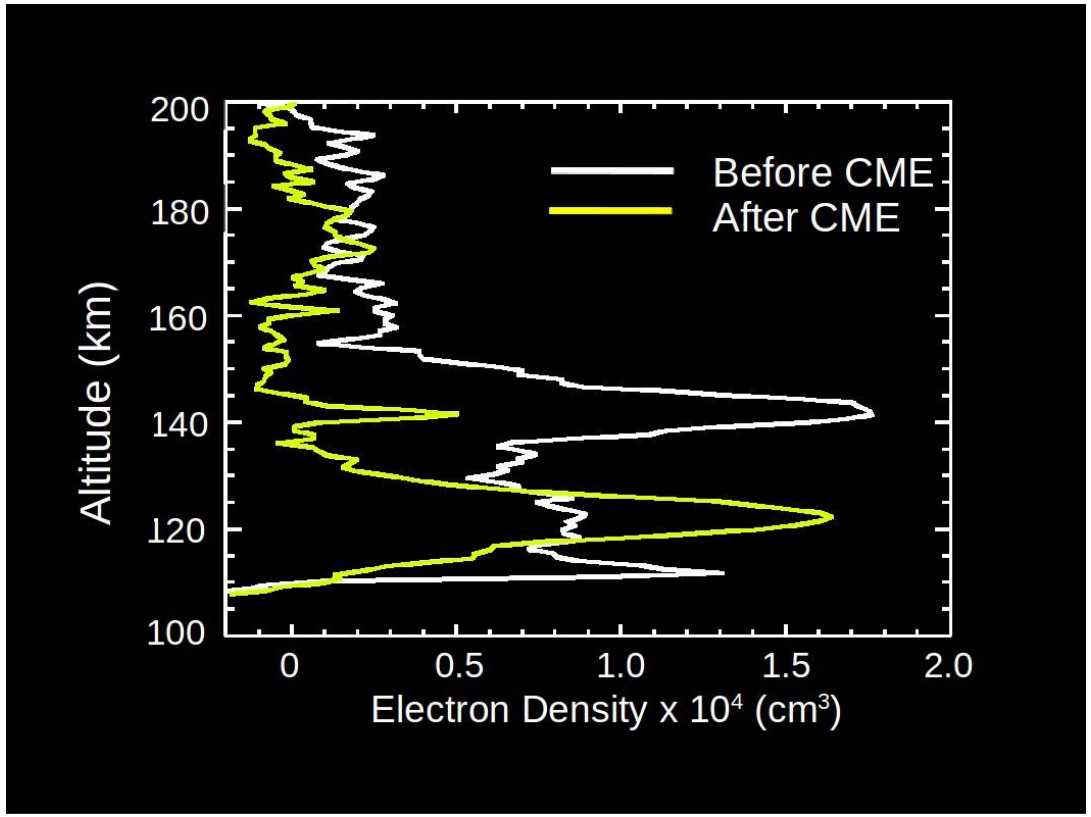
Space weather: internal planets in solar system

Venus – suspected auroras

- atmosphere (incl. ionosphere)
- **no** large-scale magnetic field



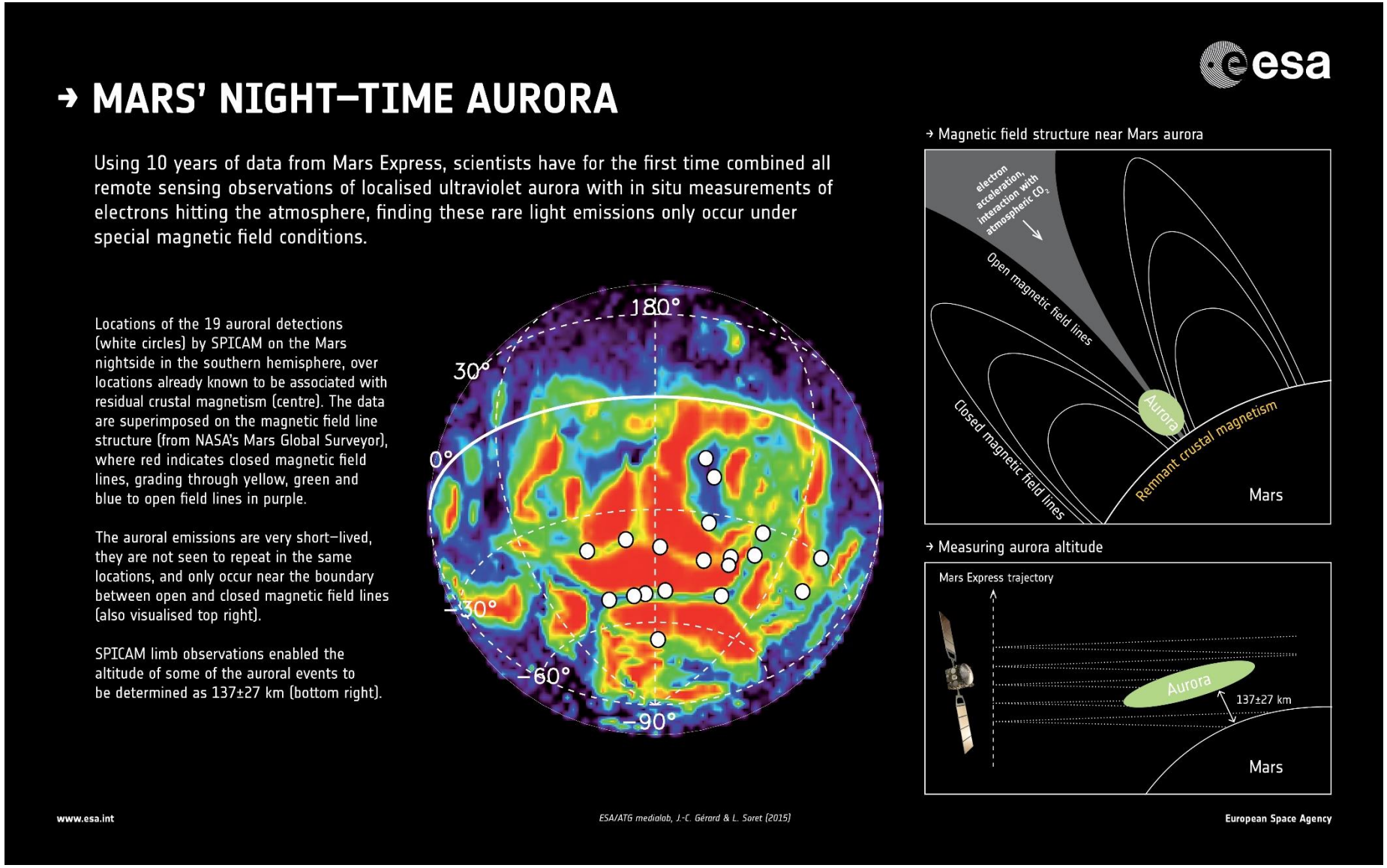
http://earthsky.org



DPS press release/C. Gray/New Mexico State University

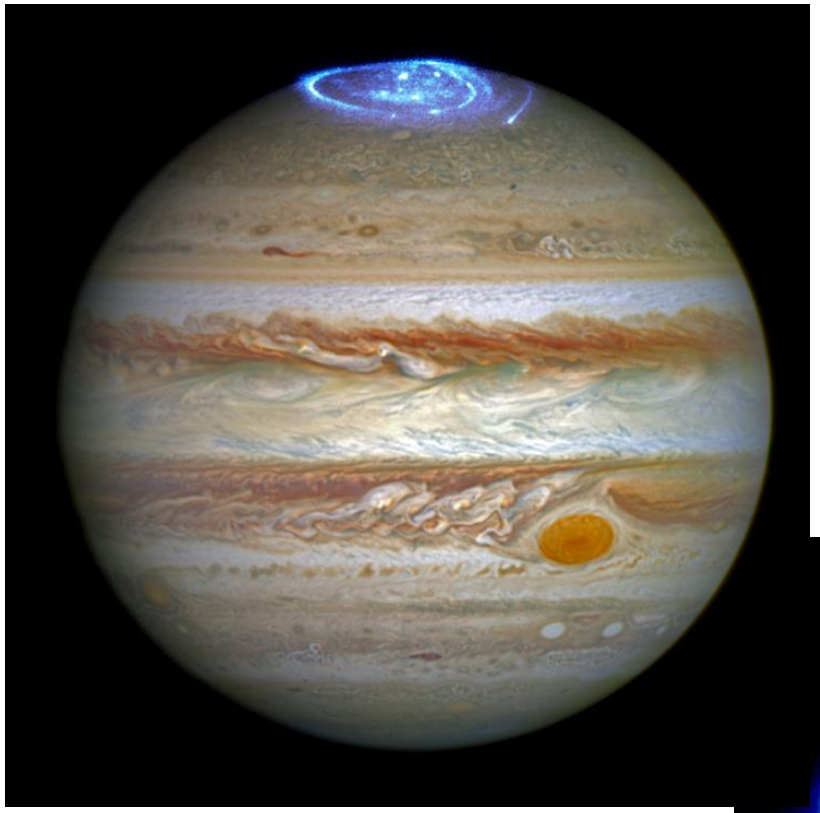
Space weather: internal planets in solar system

- thin atmosphere
- **no** global magnetic field (only local, due to surface rocks)



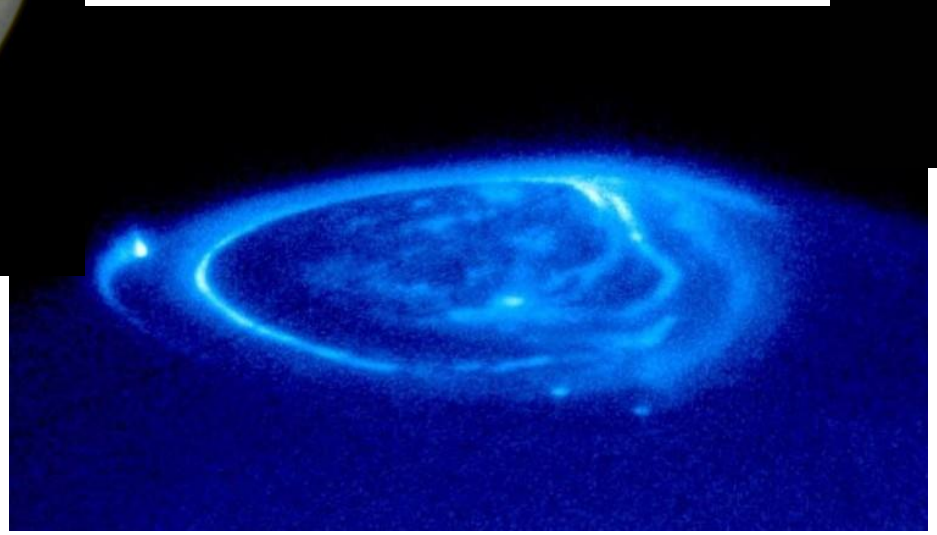
Space weather: external planets in solar system

Jupiter



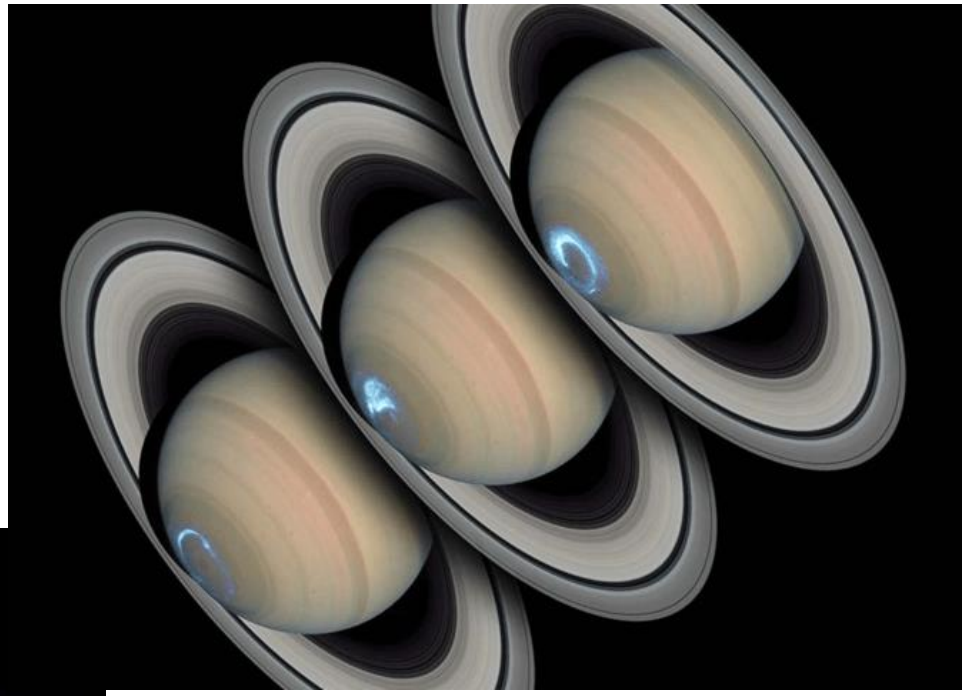
NASA/ESA/Hubble

Jupiter



NASA/ESA/Hubble/J. Clarke

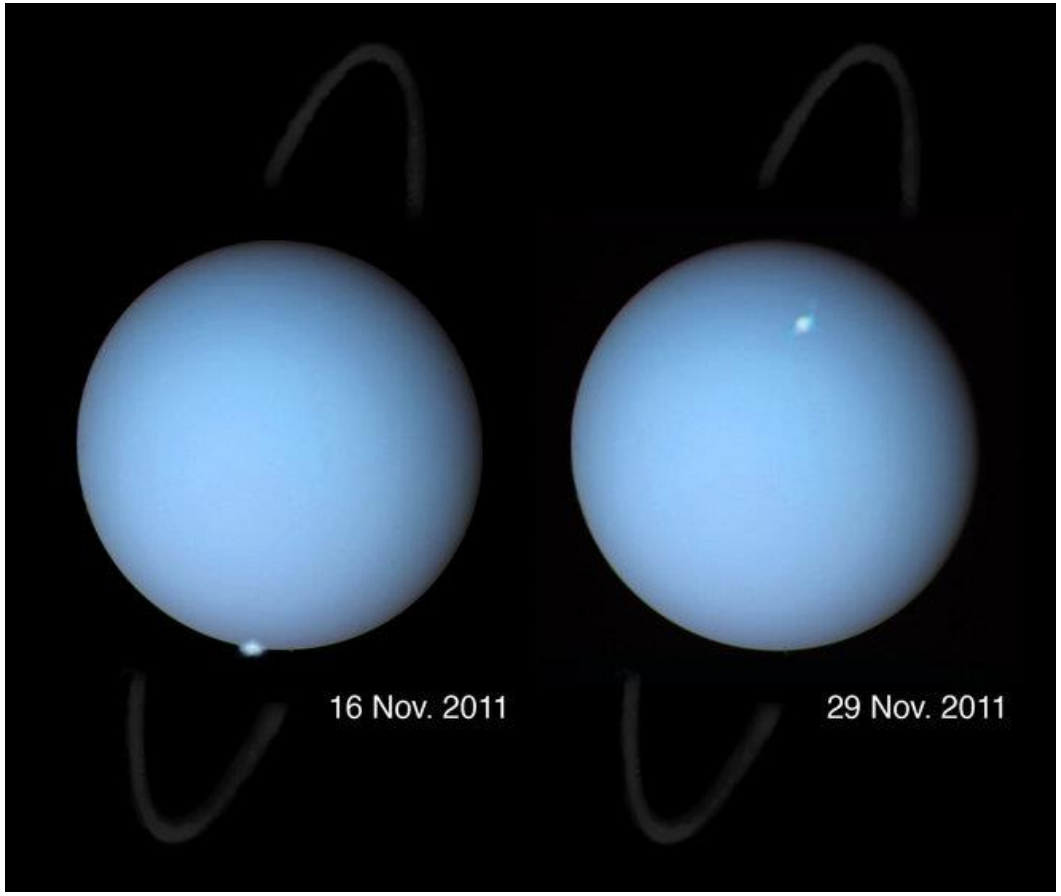
Saturn



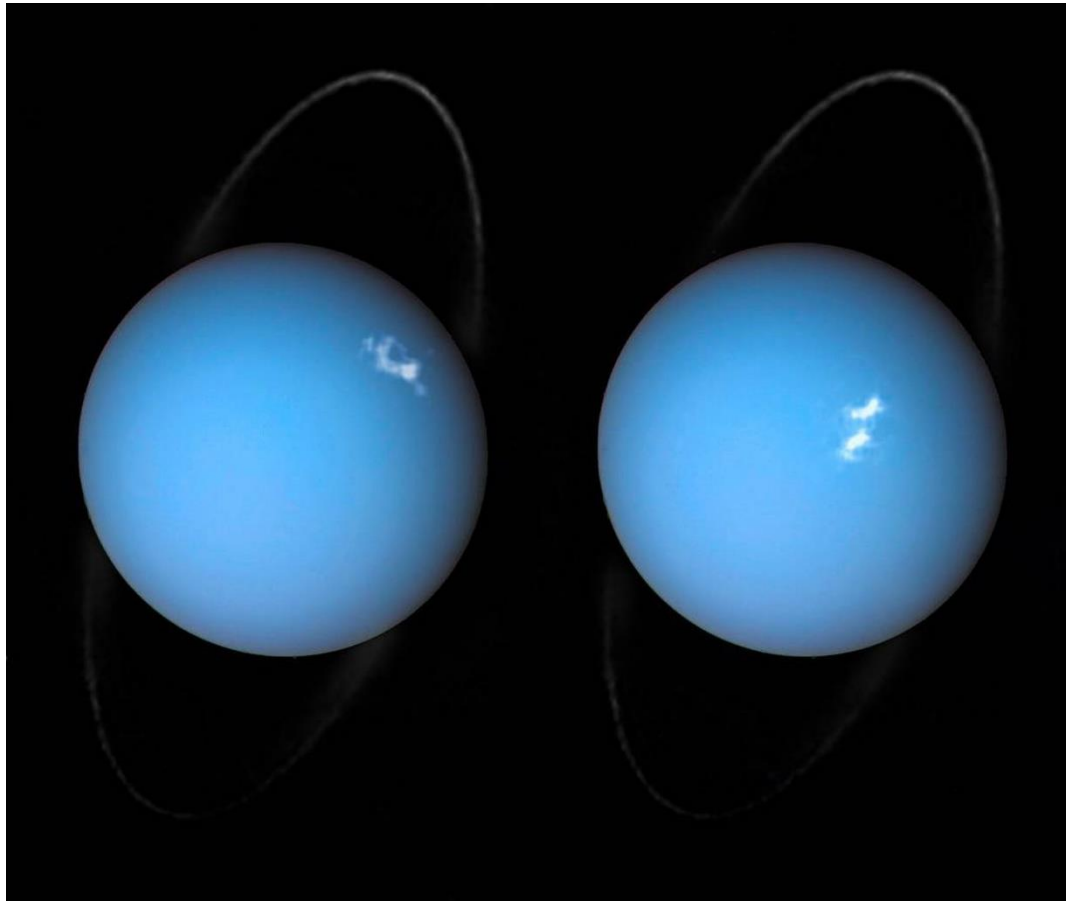
NASA/ESA/Hubble

Space weather: external planets in solar system

Uranus



NASA/ESA/Hubble
Laurent Lamy



NASA/ESA/Hubble **2012 & 2014**
Voyager 2

Space weather: exoplanets

Brown dwarf with red aurora

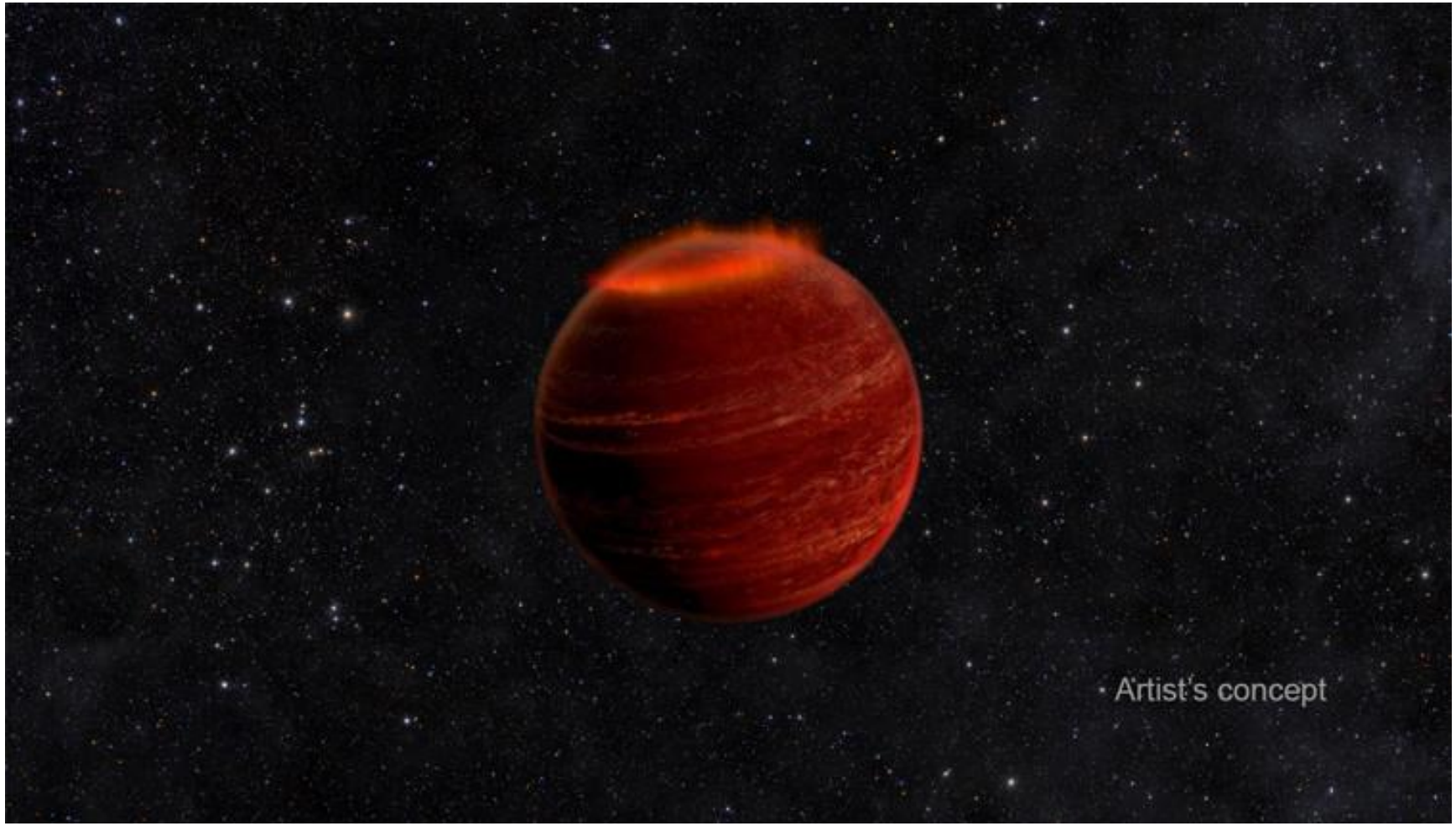


Image: Chuck Carter and Gregg Hallinan
Hallinan et al. (2015) Nature
http://www.nature.com/nature/journal/v523/n7562/full/nature14619.html

A new method for exoplanet search?

Space weather: multi-disciplinary research

Solar physics

Earth research
- Magnetosphere
- Atmosphere
- Climate

Engineering
- space
- ground-based

Solar system

Human space travel

Exoplanets

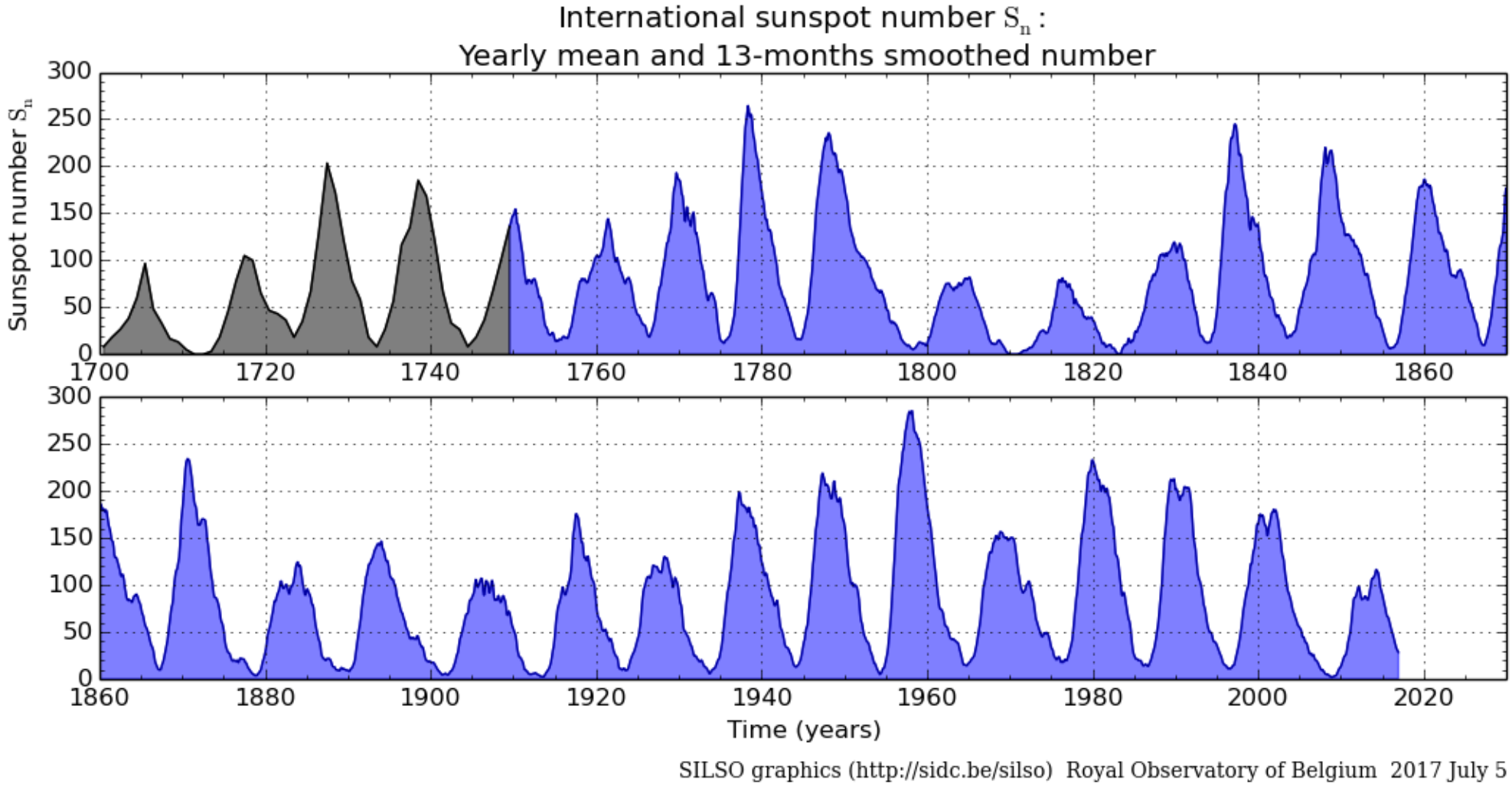
European Forum

Fourteenth European Space Weather Week

27 Nov–1 Dec 2017, Ostend, Belgium

http://www.stce.be/esww14/

Space climate: long-term effects



No long-termed record of earth temperature, sea temperature, solar radiation – reconstructions!

Space climate: long-term effects

Haigh, Liv. Rev. Solar Physics, 4, 2007, 2

"**Radiation from the Sun** – the only energy source for the Earth's atmosphere **and changes in solar activity clearly have the potential to affect climate**.

There is **statistical evidence for solar influence** on various meteorological parameters on all timescales, although **extracting the signal from the noise** in a naturally highly variable system **remains a key problem**.

Changes in total solar irradiance undoubtedly impact the Earth's energy balance but **uncertainties in the historical record** of TSI mean that **the magnitude of even this direct influence is not well known**.

Variations in solar UV radiation impact the thermal structure and composition of the middle atmosphere but **details of the responses in both temperature and ozone concentrations are not well established**.

Various theories are now being developed for coupling mechanisms whereby direct solar impacts on the middle atmosphere might influence the troposphere but **the influences are complex and non-linear** and **many questions remain** concerning the detailed mechanisms which determine to what extent, where and when the solar influence is felt.

Variations in cosmic radiation, modulated by solar activity, are **manifest in changes in atmospheric ionization** but **it is not yet clear whether these have the potential to significantly affect the atmosphere in a way that will impact climate**."

10th International Workshop

Space Influences on the Magnetosphere, Ionosphere and Atmosphere

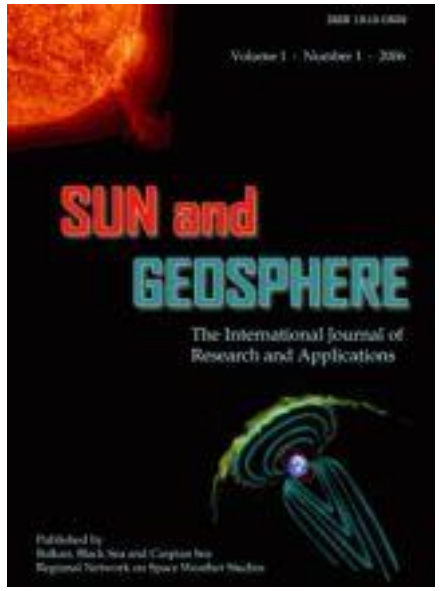
May–June 2018

http://ws-sozopol.stil.bas.bg/

LOC: Space Climate Group (SRTI-BAS) **www.space.bas.bg**

Topics

- ✓ **Sun and solar activity**
- ✓ **Solar wind-magnetosphere-ionosphere**
- ✓ **Solar influences on the lower atmosphere and climate**
- ✓ **Solar effects in the biosphere**
- ✓ **Instrumentation for space weather monitoring**
- ✓ **Data processing and modelling**



Publications on space weather topics:

http://sungeosphere.org/