Space Weather

Earth, neighboring planets and exoplanets

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Near-Earth space weather (1/2)

Space weather refers to conditions on the Sun and in the space environment that can:

- influence the performance and reliability of technology (space-borne and ground-based)

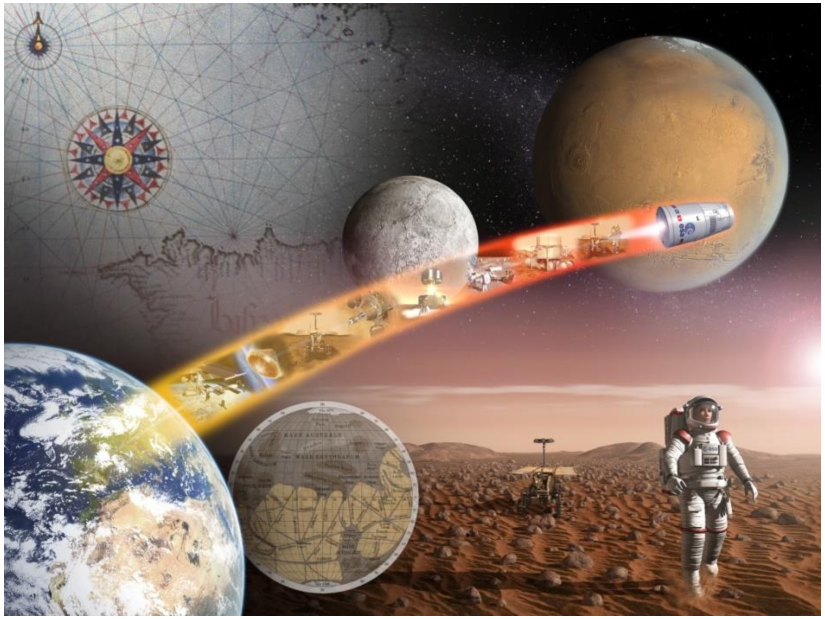
- endanger human life and health.

Near-Earth space weather (2/2)

Local space weather = function (
- Location in the Solar System.
- Behavior of the Sun
- Nature of Earth's magnetic field and atmosphere.

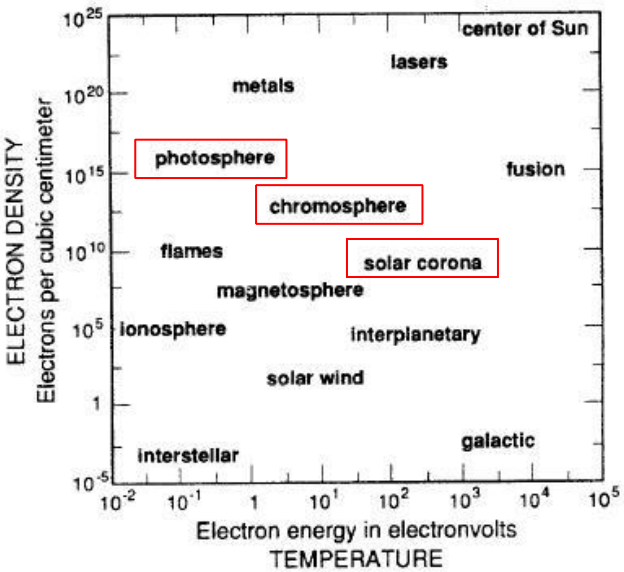
)

For inter-planetary travel spacecraft encounter and must survive:
- ultra-high vacuum
- extremes of hot (sunward side) and cold (shadow side or in the outer solar system) temperatures
- hostile space weather induced environments
    - can severely limit space missions as well as pose threats to humans.

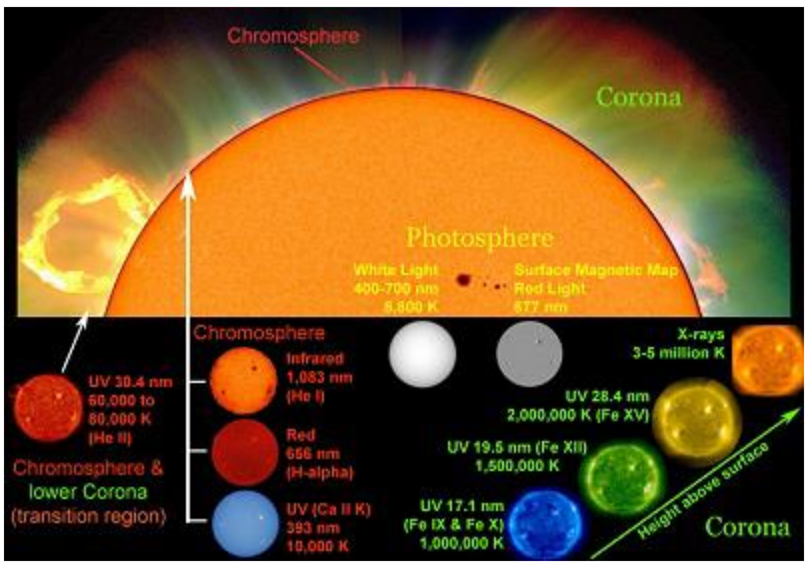


Credit: ESA

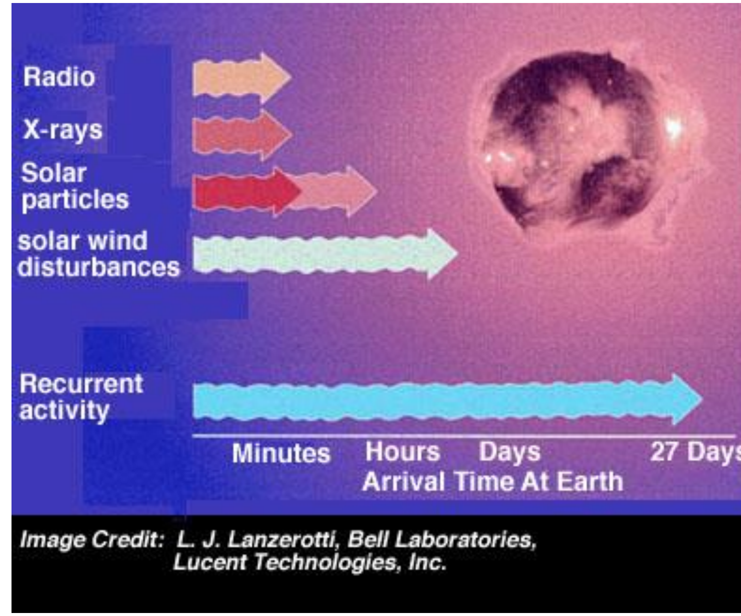
Our nearest star the Sun drives the local space weather



Peratt (1996)



Composite image courtesy of Windows to the Universe using images from SOHO (NASA and ESA), NCAR/HAO/MLSO, Big Bear Solar Observatory, and SDO/AIA.



Solar-Terrestrial Physics	Space Weather
Basic research	Application oriented
Scientific observations	Continuous monitoring
Scientific products	Service products

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THE ASTROPARTICLE PHYSICS CONFERENCE

sub-topics of Astroparticle Physics:

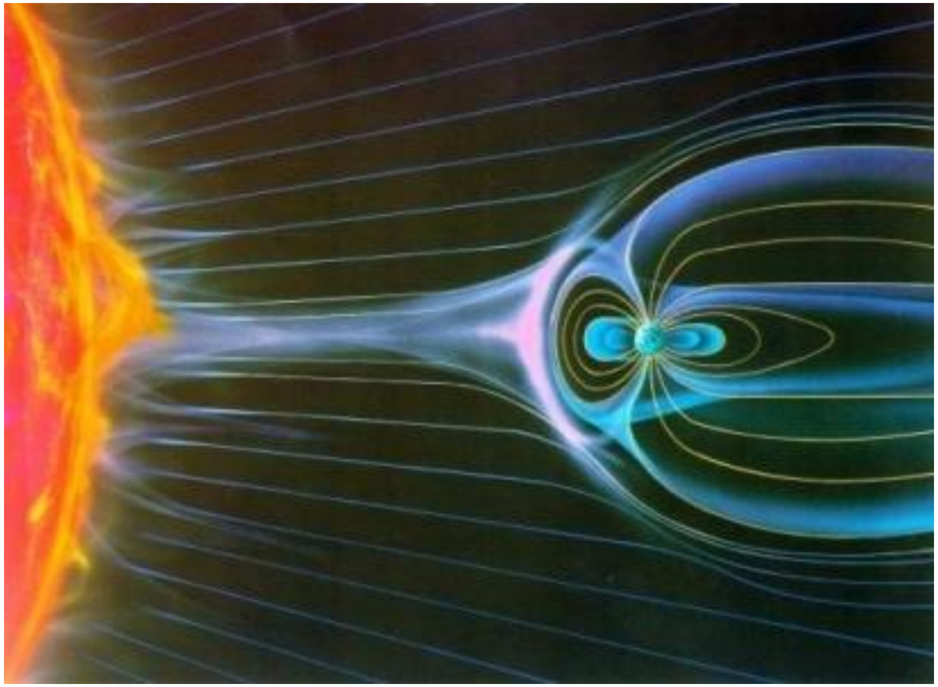
- Cosmic Ray Physics
- Gamma Ray Astronomy
- Neutrino Astronomy & Physics
- Dark Matter Physics
- Solar & Heliospheric Physics

Space high-energy particle radiation:

- Trapped Particle Populations
- Galactic Cosmic Rays
- Solar Energetic Particles

Golberg (1961)

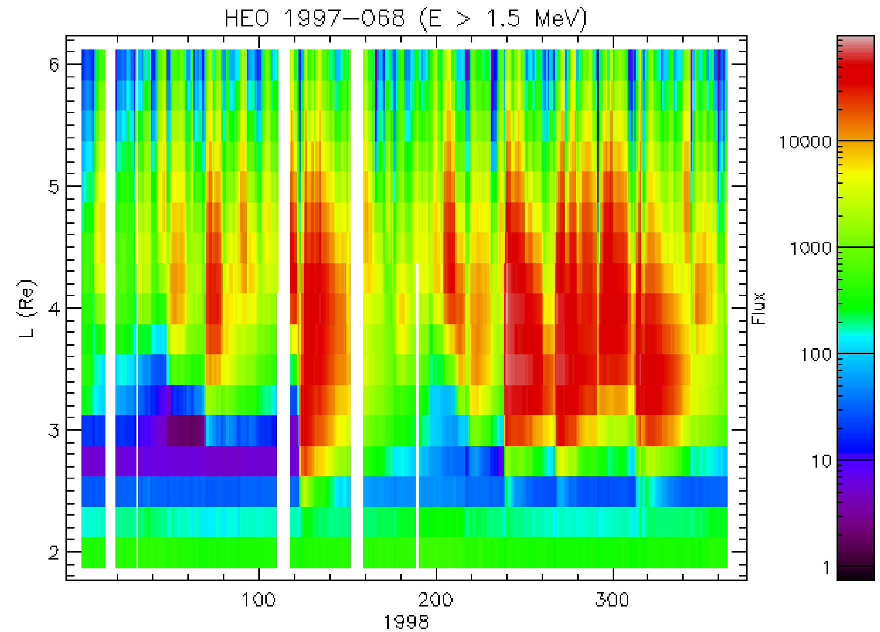
Trapped Particle Populations



Copyright: NASA

Earth’s Radiation Belts

McIlwain L-parameter describes a particular set of planetary magnetic field lines (L =2 is two Earth radii from Earth’s centre)



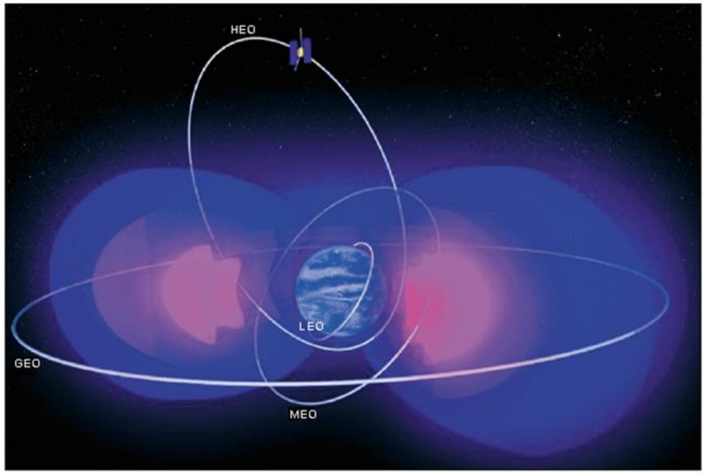
Daily Averaged Electron Outer Radiation Belt Count Rate Data
(HEO data courtesy of The Aerospace Corporation)

Protons

- Inner Belt: 1.3 R_E
- tens keV - couple of hundreds of MeV
- Fairly stable in time

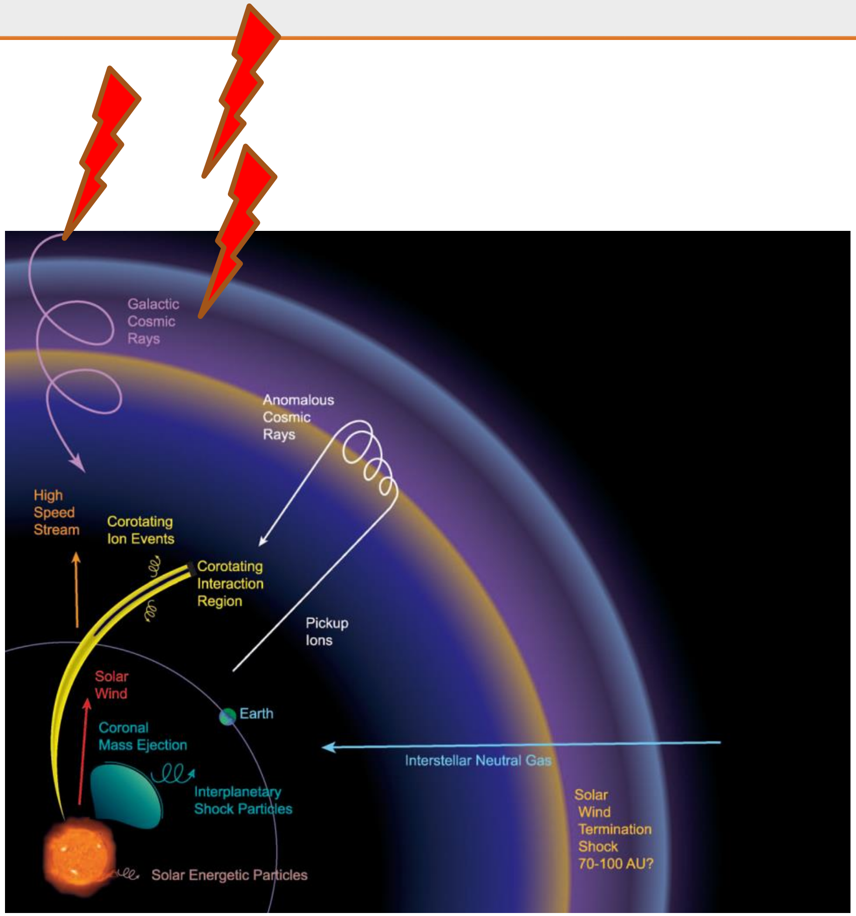
Electrons

- Inner Belt: 1.5 - 2.5 R_E
- Outer Belt: 3-9 R_E
- tens keV - several MeV
- Variations ‘minutes-years’



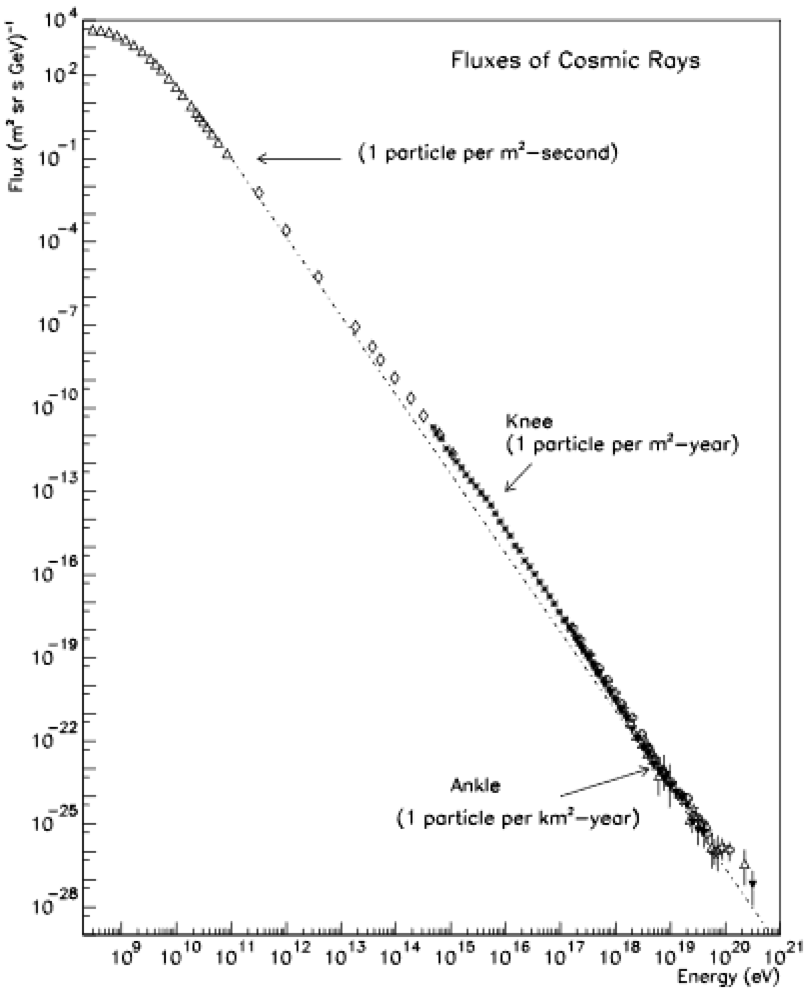
The Van Allen radiation belts and typical satellite orbits. Key: GEO—geosynchronous orbit; HEO—highly elliptical orbit; MEO—medium Earth orbit; LEO—low Earth orbit. (Illustration by B. Jones, P. Fuqua, J. Barrie, The Aerospace Corporation.)

Galactic Cosmic Rays



Credit: ACE/NASA

Galactic Cosmic Rays (GCRs) (1/2)



Swordy (2001)

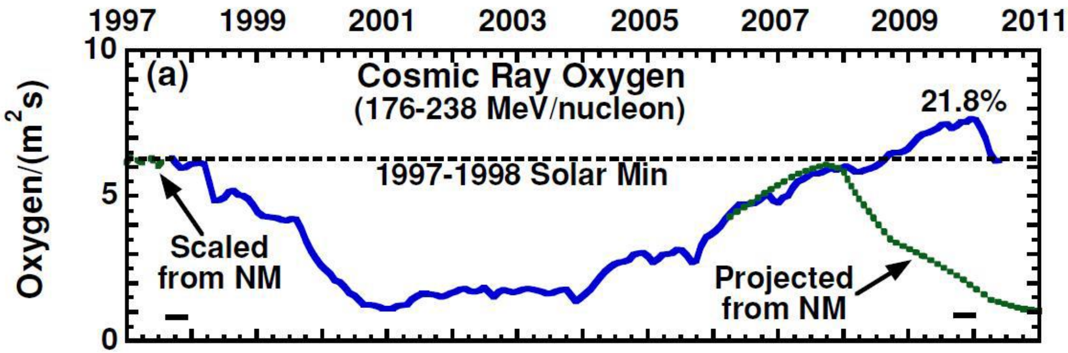
- In general the differential energy spectrum of GCRs has a power-law like behavior for many orders of magnitude.
- GCRs are VERY high-energy particles [0.1 – 1000 GeV]
  - 100 to 1000 MeV fluxes constitute the largest contribution.
- Sources
  - supernovae
  - active galactic nuclei, quasars, gamma-ray bursts, …
- GCRs collide (interact) with atmospheric nuclei creating air showers.

Galactic Cosmic Rays (GCRs) (2/2)

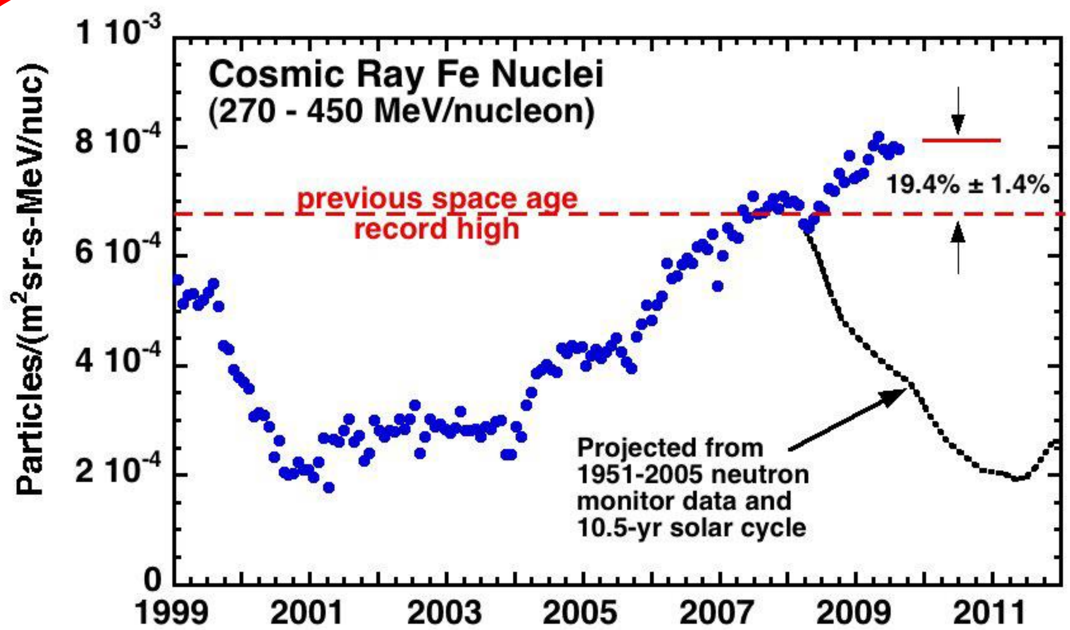
GCR flux is modulated by solar activity

- As a first approximation the GCR background intensity can be said to be slowly varying and therefore predictable over short timescales.

However, …..



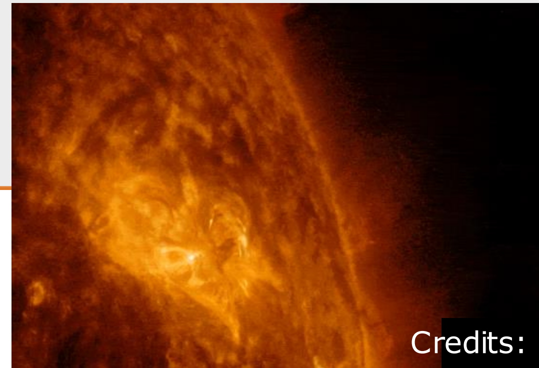
Credit: Mewaldt et al. (2010)

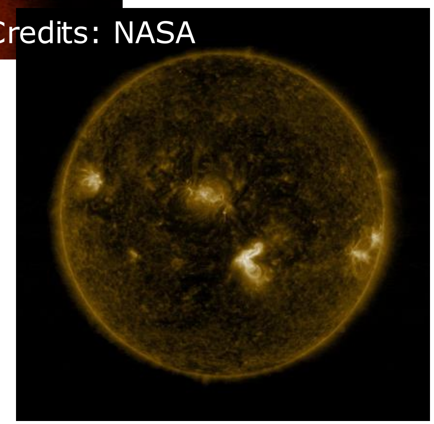


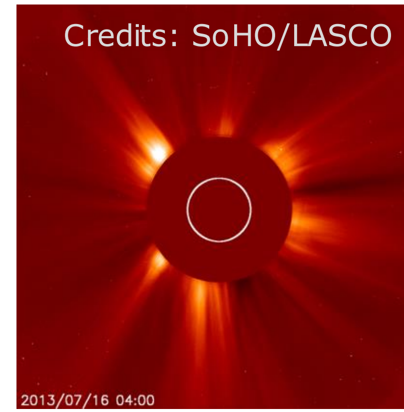
Credit: Richard Mewaldt/Caltech

Solar Energetic Particle (SEP) Events

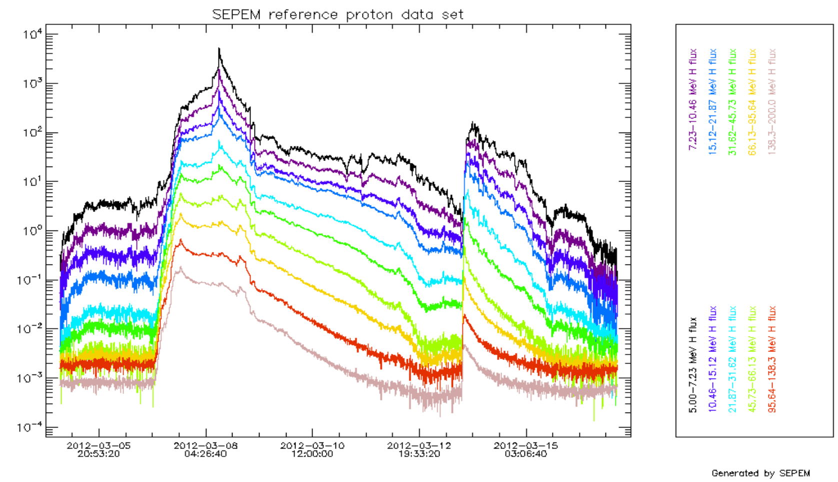
SEP events



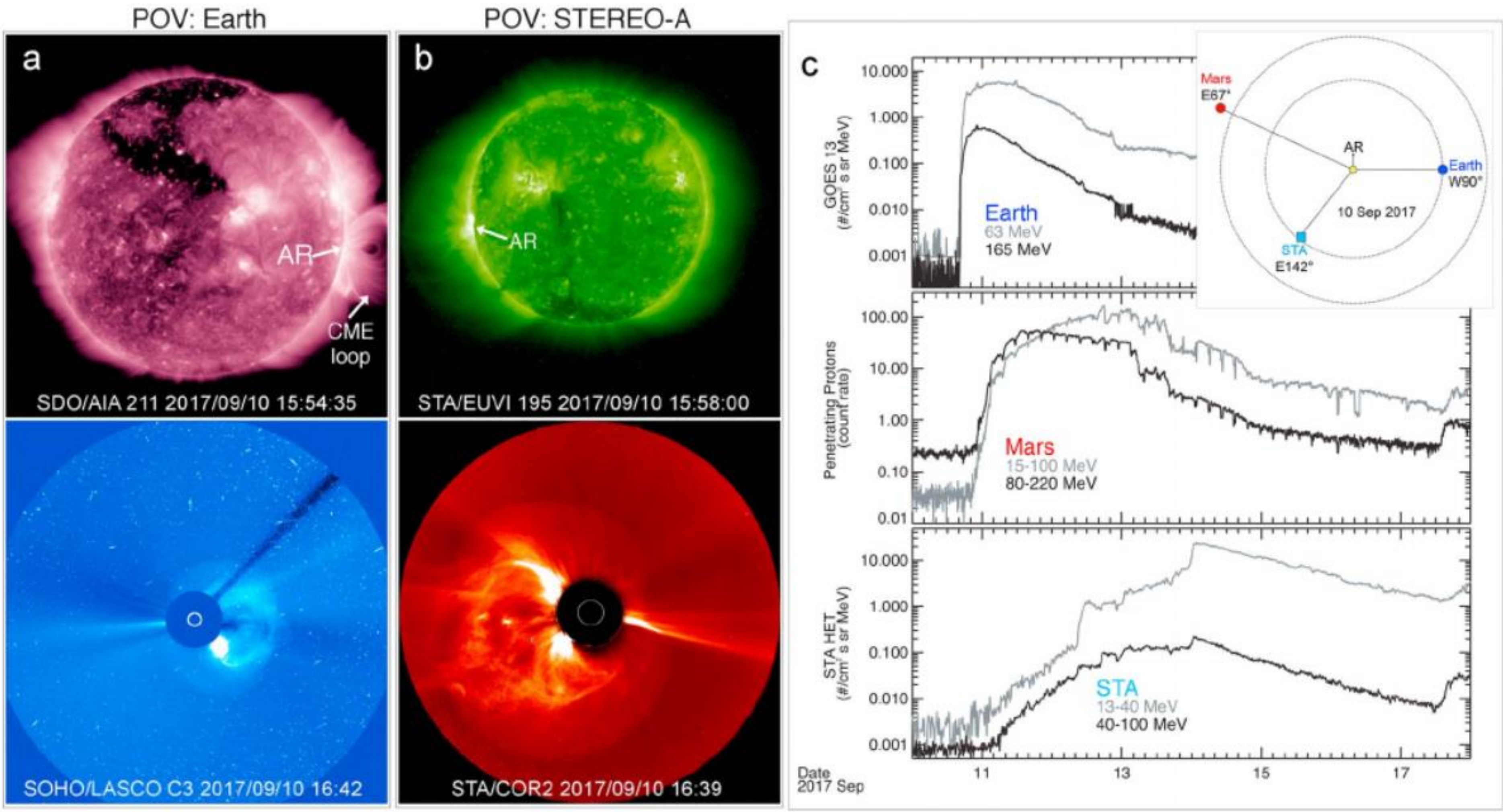




- Associated with solar flares and/or the shock waves driven by coronal mass ejections.
- Mainly comprised of protons, electrons, and α-particles with small contributions of 3He-nuclei and heavier ions up to iron.
- Sporadic with energies from tens of keV to a few GeV.
- Flux increase of several orders of magnitude over the course of tens of minutes to hours or even a day.
- May last from minutes to days or weeks (depending on the energy of interest).

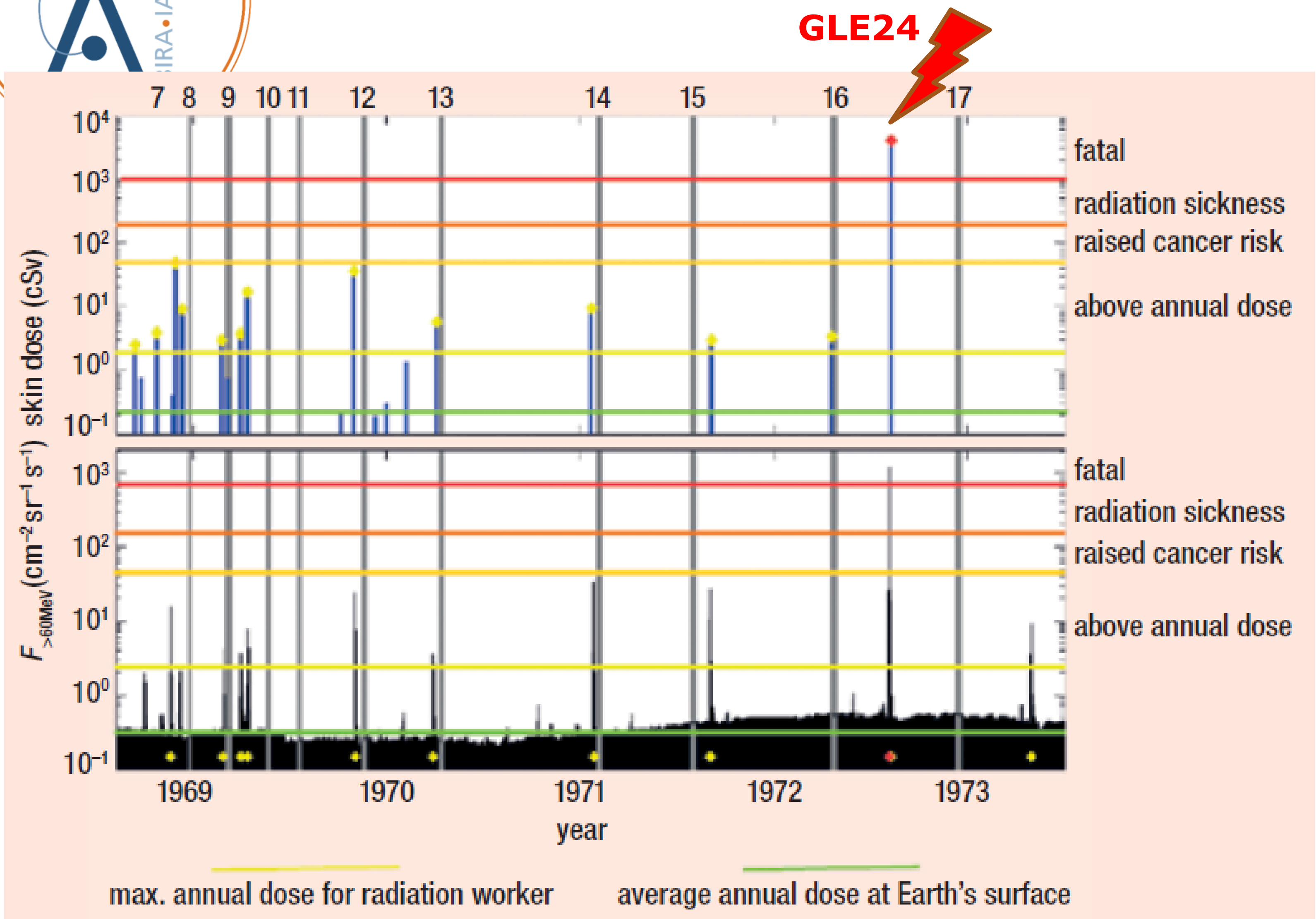


10 September 2017 solar events



Lee, Jakosky, Luhmann, et al. (2018)

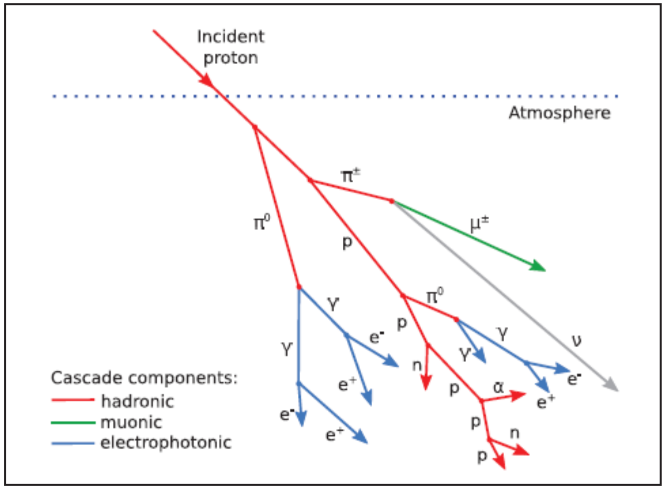
Apollo missions and SEP events



M. Lockwood, and M.A. Hapgood (2007)

Ground Level Enhancement (GLE) events (1/2)

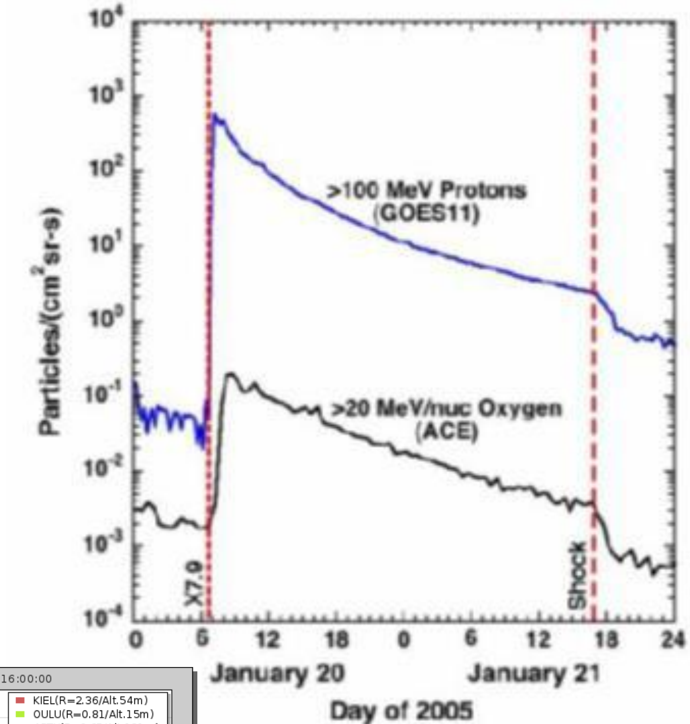
- GLEs form a particular case of high-energy SEP events associated with GeV protons.
- Typically associated with solar eruptive events (flares and/or CMEs) occurring near the western limb of the solar disk, where it is magnetically connected to Earth via IMF field lines.
- Accelerated SEPs have energies sufficiently high to penetrate along the geomagnetic field and the Earth's atmosphere.
- SEPs must possess sufficient energy to initiate an atmospheric nucleonic cascade, which can reach the ground.

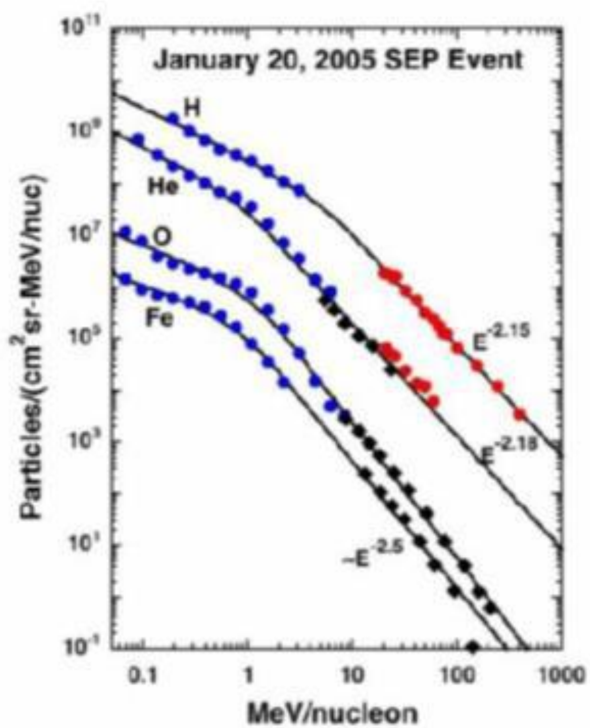


Miyake, Usoskin & Poluianov (2020)

- Ground-based neutron monitors observe GLE events.

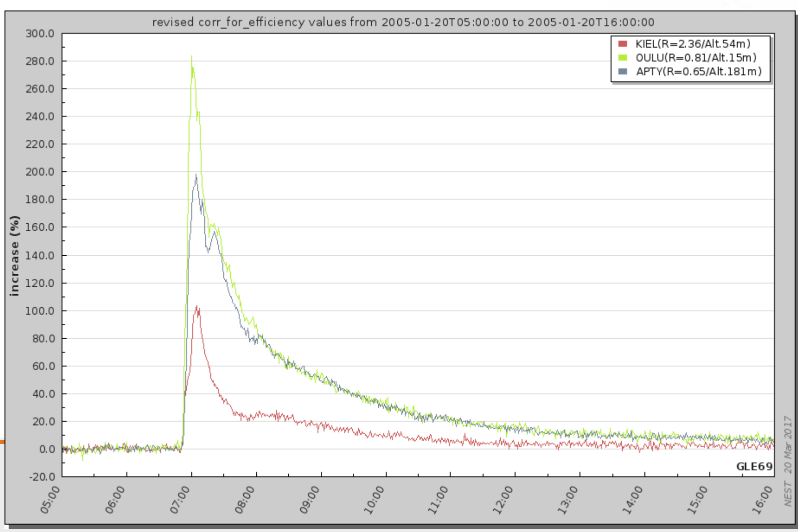
Ground Level Enhancement (GLE) events (2/2)





Credit:
ACE News

Credit: NMDB database
(www.nmdb.eu)



GLE69
Onset date/time: 2005-01-20, 06:51:00

GLE events and their effects on Earth

Can increase the radiation hazard to avionics (e.g. single event effects in micro-electronic devices).

Increases the radiation dose received by humans flying at high altitude and/ or geographic latitudes, for example:

- high-latitude flights (>50°N)
- polar routes (>78°N)

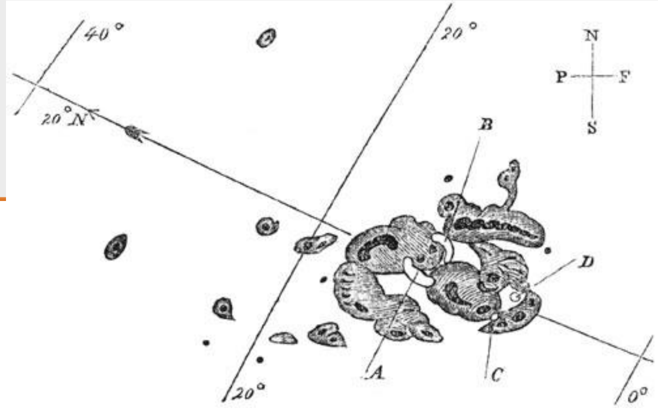
→ In summary, the farther north or south you are from the Equator the more radiation you will receive.

In regard to commercial aviation can be a risk for frequent flyers and particularly for aircrew.

Carrington Event

Solar storm of 1859

The associated "white light flare" in the solar photosphere was observed and recorded by British astronomers Richard C. Carrington (1826–1875) and Richard Hodgson (1804–1872).



Richard C. Carrington (1859)

ENERGY RANGE	EFFECTS
Superstorm radiation	Systems with very high safety and reliability requirements (e.g., in the nuclear power industry) may need to take account of superstorm ground level radiation on microelectronic devices within the system.

"In the case of nuclear power a Carrington event may not be a sufficient case since relevant timescales for risk assessment may be as long as 10,000 years."

(Paul Cannon, Extreme space weather: impacts on engineered systems and infrastructure, 2013)

Multi-scale phenomena
an introduction

The Earth and Solar System are full of multi-scale phenomena. What do all these natural dynamic phenomena have in common?:

1. They obey nonlinear spatio-temporal scaling laws.

2. Size distributions (on log-scale) of parameters describing the phenomena (energies, etc.) cover many orders of magnitude.

3. Powerlaw-like behavior has been found to be a universal characteristic of such phenomena.

Super extreme solar events
How to study these possible rare events?

Direct measurements limited to:

- several decades (particle and electromagnetic measurements)
- over a century (solar images and measurements of geomagnetic indices)

Indirect ways to study (search for) super extreme events

- indirect proxy methods (e.g., cosmogenic isotopes)
- observing Sun-like stars (e.g., stellar flares)

“Extreme Solar Particle Storms: The hostile Sun”, Fusa Miyake, Ilya Usoskin, and Stepan Poluianov (Eds.), IOP Publishing, 2020

The 775 AD cosmic event:
cosmogenic isotopes

Miyake et al. (Nature, 2012) found a significant enhancement of about 1.5% (15 permill) of ^{14}C content measured in Japanese cedars from around 775 AD.

Usoskin et al. (2013) confirmed the existence of the 775 AD event by new measurements of ^{14}C in German oak and by the existing ^{10}Be data from polar ice cores. Interpreted the ^{14}C measurements using an appropriate carbon cycle model and surveyed available historical chronicles for astronomical observations. Results pointed to the likely solar origin of the event.

Solar origin of the 775 AD event was fully confirmed by a multi-proxy analysis by Mekhaldi et al. (Nat. Comm., 2015) and Sukhodolov et al. (Nat. Sci. Rep., 2017).

Further cosmic events:
cosmogenic isotopes

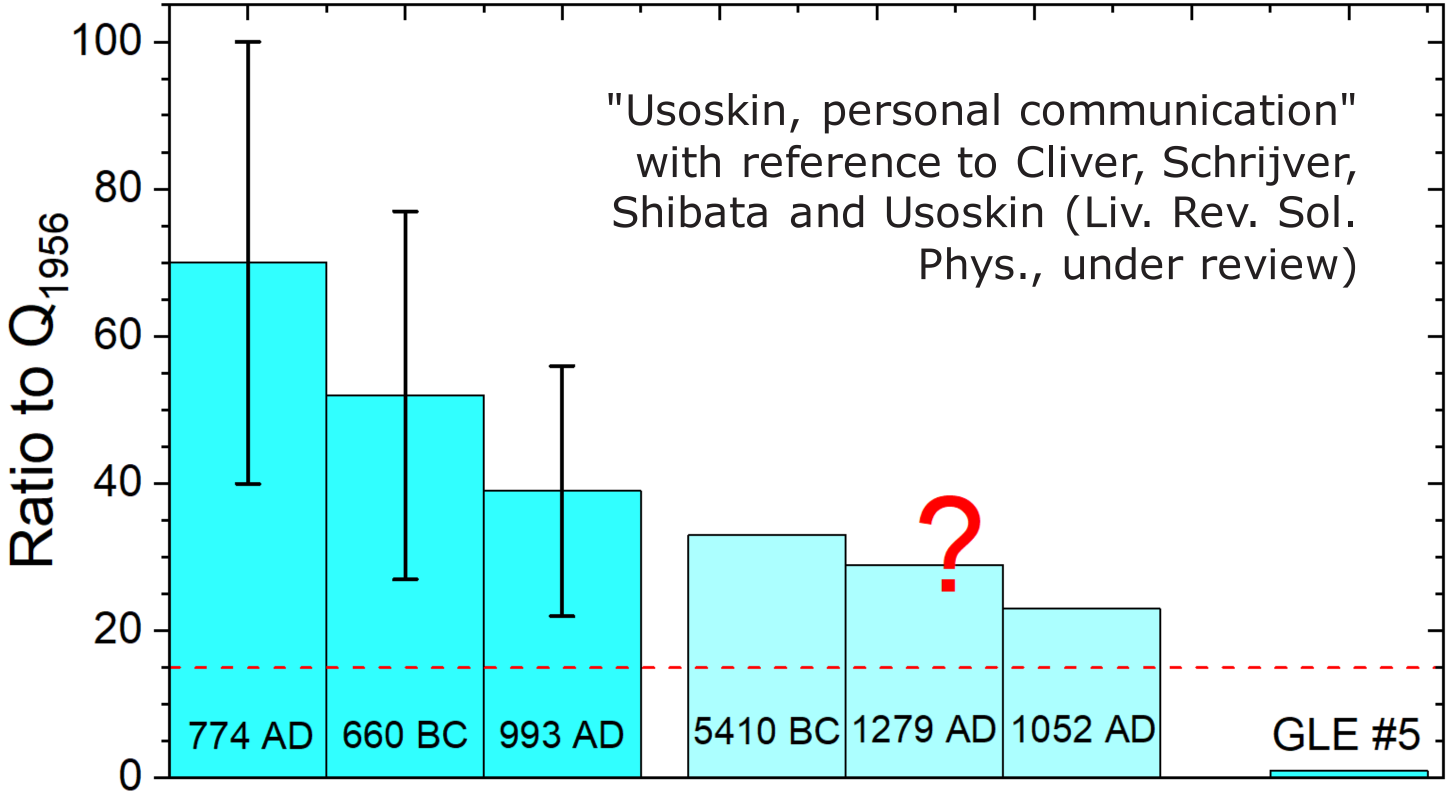
Two more events have been discovered and confirmed as SEP events

- 994 AD (Miyake et al., Nat. Comm., 2013)
- 660 BC (O'Hare et al., PNAS, 2019).

All confirmed events have hard energy spectra (Mekhaldi et al., 2015; Sukhodolov et al., 2017: O'Hare et al., 2019), similar to that of the largest directly known solar particle event of 23-Feb-1956 (GLE5).

Recently, three more event candidates have been discovered (not fully analyzed):

- 1052 AD and 1279 AD (Brehm et al., Nat. Geosci., 2021)
- 5410 BC (Miyake et al., GRL, 2021).



Red question mark denotes the three recent event candidates

GLE #5 (1956 Feb. 23): strongest GLE event ever recorded

- Events are compared in the amount of ^{14}C produced (measured for historical events and computed theoretically for the GLE5 event).
- Threshold value (dotted red line) suggests that events weaker than 15x GLE5 cannot be reliably detected by a single ^{14}C dataset.
- Error bars are defined by both the measurement uncertainties of ^{14}C in tree rings and model uncertainties of the carbon cycle

Superflares and giant planets

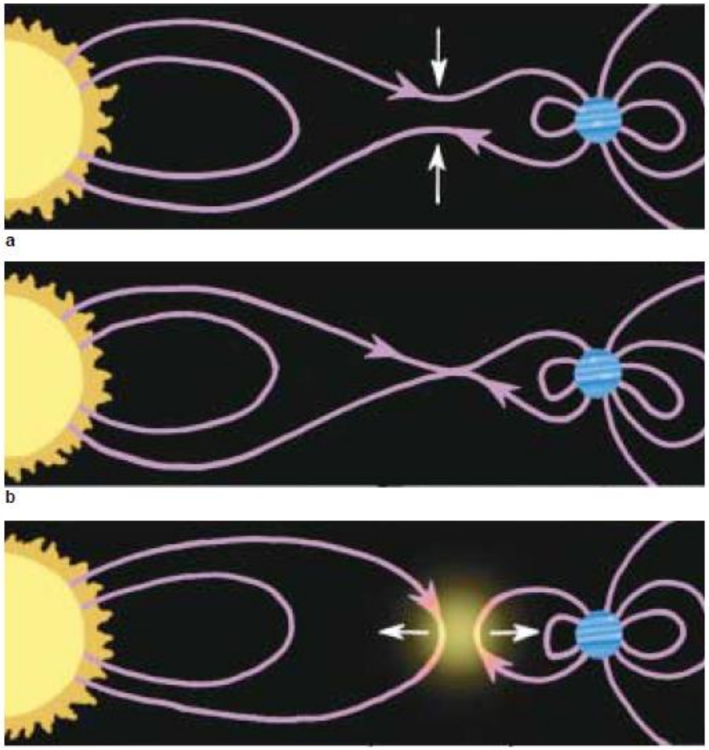
G-type main-sequence stars: Sun-like stars (surface temperature 5600–6000 K and slowly rotating with a period longer than 10 days)

9 superflares on normal solar-type stars were discovered by Schaefer, King, and Deliyannis (2000)

- solar analogues have large stellar flares
- could the Sun also experience such an event?

Rubenstein and Schaefer (2000):

- suggested that solar type stars with a hot Jupiter companion are good candidates for superflare stars.
- proposed that the Sun would never produce superflares since our Sun does not have a hot Jupiter.



Eric P. Rubenstein (2001)

Superflares (1/2)

Kepler Space Telescope (2009 - 2018)

- many superflares on solar-type stars were found from Kepler data

Maehara et al., (Nature, 2012) discovered and analyzed the statistical properties of 365 superflares (10^{33}–10^{36} erg) on 148 solar-type stars.

1. The occurrence rate of these superflares as a function of their total energy is quite similar to that of solar flares ($dN/dE \propto E^{-\alpha}$, $\alpha \sim 2$).
2. These superflare stars show quasi-periodic brightness variation, which may be evidence of very big starspots with stellar rotation.
3. It is found that superflares occur on Sun-like stars with frequency such that superflares with energy 10^{34} erg (occur once every 800 yr) and 10^{35} erg (occur once every 5000 yr).
4. *There is no hot Jupiter around these superflare stars, suggesting that hot Jupiters are rare in superflare stars.*

Shibayama, Maehara, et al. (2013) extended the Maehara et al. (2012) study to1547 superflares on 279 G-type dwarfs.

- Proposed the origin of superflares to the existence of extremely large starspots.

Davenport (2015) presented the first automated search for stellar flares from the full Kepler data set and found from 4041 stars using Kepler light curves the average flare energy detected to be $\sim 10^{35}$ erg.

Superflares (2/2)

Shibata et al. (2013) examined whether superflares with energy of 10^{33}–10^{35} erg could occur on the present Sun.

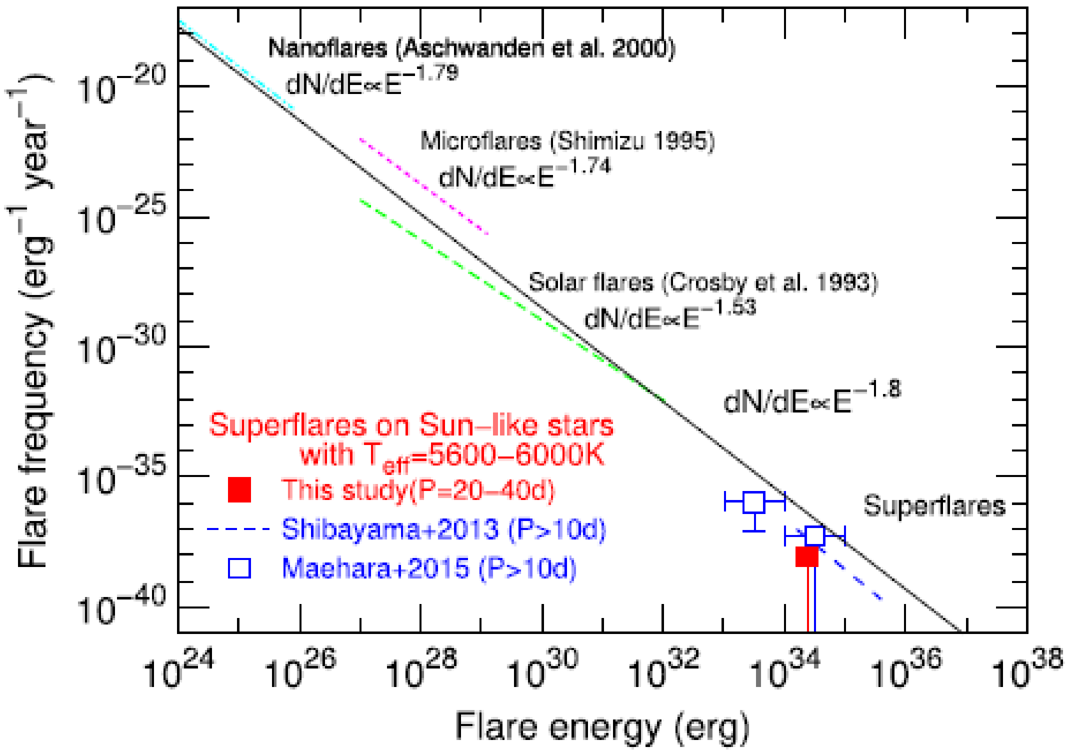
- Used simple order-of-magnitude estimates assumed in typical dynamo models – magnetic flux is generated by differential rotation at the base of the convection zone.
- Found that it is possible that the present Sun would generate a large sunspot to store sufficient magnetic flux for generating superflares with an energy of:
    - 10^{34} erg (within one solar cycle period)
    - 10^{35} erg (would take ~ 40 yr)

Notsu et al. (2019) found:

- superflares with energies $<5\times10^{34}$ erg occur on old, slowly rotating Sun-like stars (P_{rot} ~ 25 days) approximately once every 2000–3000 yr
- rapidly rotating stars with P_{rot} ~ a few days have superflares up to 10^{36} erg.

Superflares and solar flares

How to compare?



Notsu et al. (2019)

Three dashed lines indicate the power-law frequency distribution of solar flares observed in:

- EUV (nanoflares)
- soft X-ray (microflares)
- hard X-ray (flares)

Blue (dashed line and open squares):

- Frequency values of superflares on the stars with P_{rot} >10 days

Red square:

- updated frequency value of superflares on the stars with P_{rot} = 20–40 days

Space Weather on Exoplanets

Habitable zone or
“Goldilocks zone”

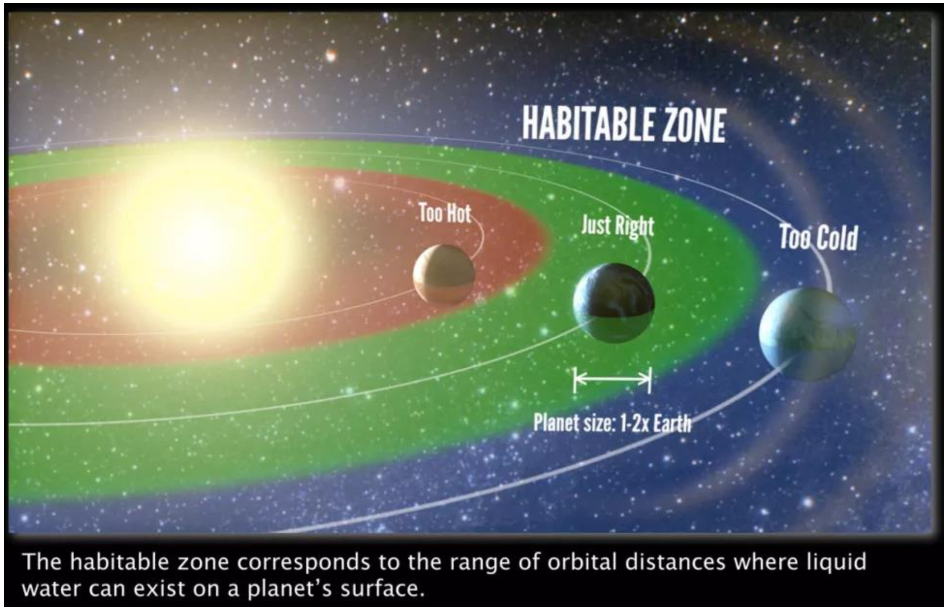
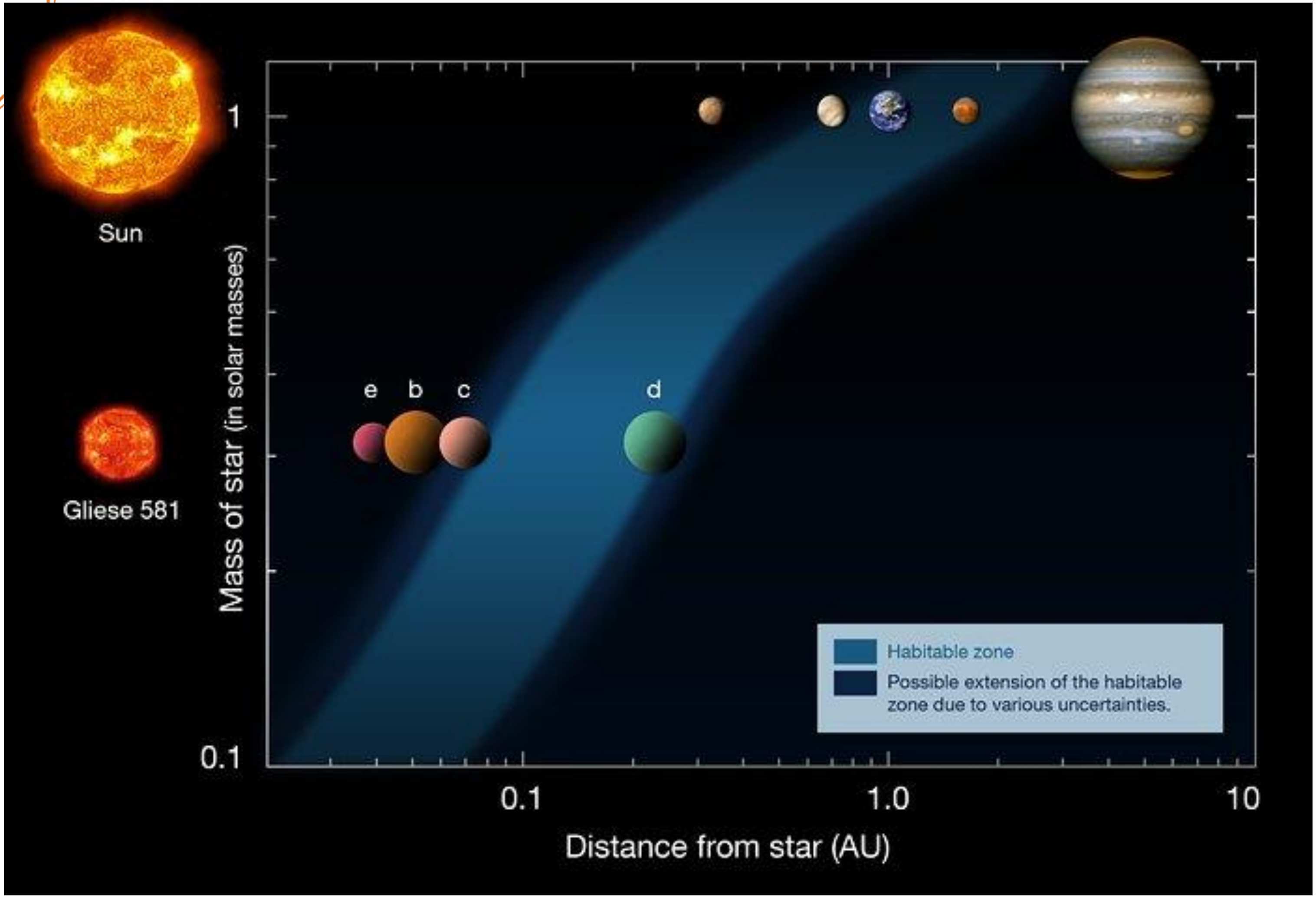


Image credit: Erik A. Petigura

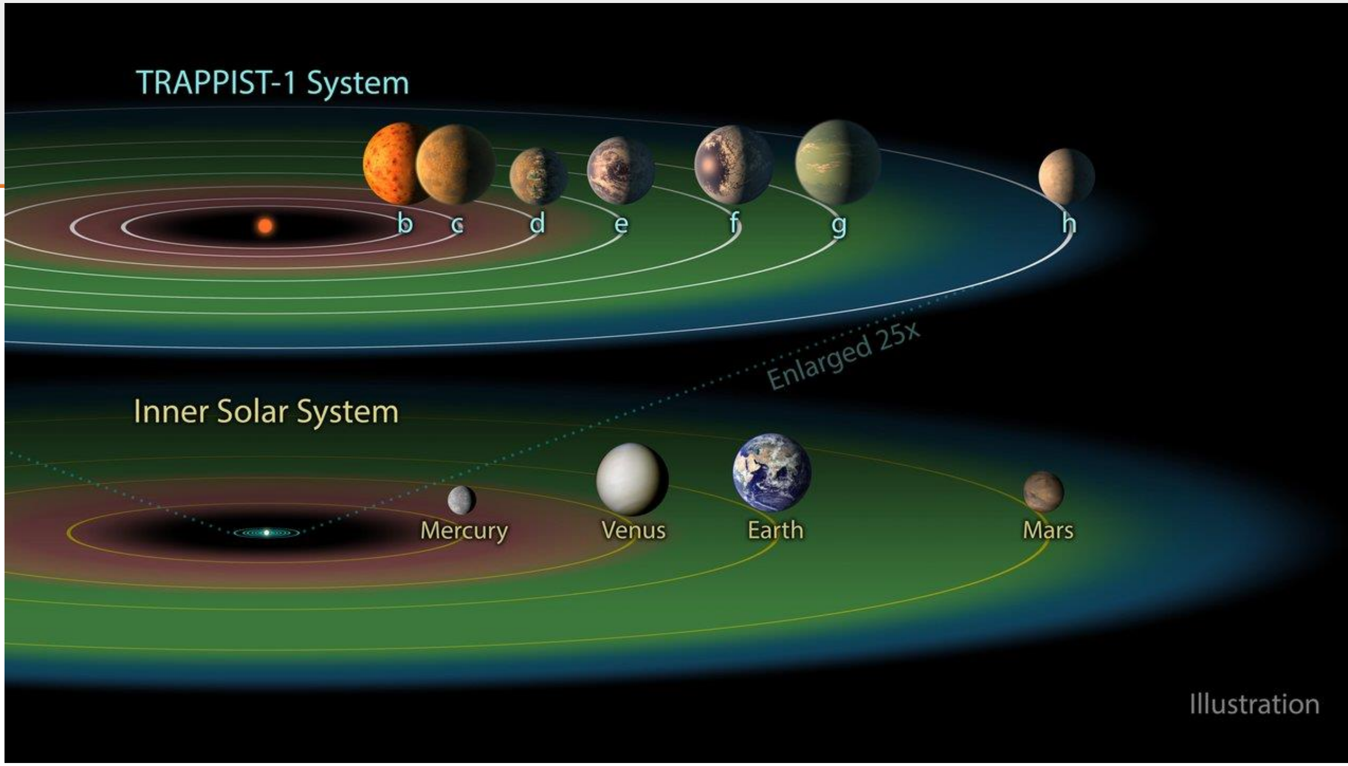
A planet in the habitable zone

It has been shown that the orbit of the planet Gliese 581 d, discovered in 2007, lies well within the habitable zone, where liquid water oceans could exist.



Credit: ESO

Stellar energetic particles



Credit: NASA/JPL-Caltech

Fraschetti et al. (2019) carried out test-particle simulations of ~GeV protons to investigate the propagation of energetic particles accelerated by flares or traveling shock waves within the stellar wind and magnetic field of a TRAPPIST-1-like system.

- Results show that TRAPPIST-1e is bombarded by a proton flux up to 6 orders of magnitude larger than experienced by the present-day Earth.

Proxima Centauri

Space weather around Sun's nearest star

Two Earth-like rocky planets orbit around Proxima Centauri, one within the habitable zone (Proxima b) where liquid water could theoretically exist on the service. (Mascareño, Faria, Figueira, et al., 2020)

"A Flare-type IV Burst Event from Proxima Centauri and Implications for Space Weather" by Zic, Lynch, et al. (2020)

- For the first time a definitive link between optical flares and radio bursts on a star that is not the Sun was shown.
- During simultaneous optical and radio monitoring of Proxima Centauri, they detected a bright, long-duration optical flare, accompanied by a series of intense, coherent radio bursts.
- Solar type IV bursts are strongly associated with space weather events such as CMEs and SEP events, suggesting that stellar type IV bursts may be used as a tracer of stellar CMEs.

Extinction events on Earth
Major and minor

Supernova possibly triggering end-Devonian extinctions

- "Supernova triggers for end-Devonian extinctions" by Fields, Melott, Ellis, et al. (2020)

Supernova and the end of the Pliocene epoch

- "^{60}Fe deposition during the late Pleistocene and the Holocene echoes past supernova activity" by Wallner, Feige, Fifield, et al. (2020)
- "Supernova-Produced 53Mn on Earth" by Korschinek, Faestermann, Poutivtsev, et al. (2020)
- "60Fe Anomaly in a Deep-Sea Manganese Crust and Implications for a Nearby Supernova Source" by Knie, Korschinek, Faestermann, et al. (2004)

Gamma-Ray burst and the end of the Ordovician epoch

- "Did a gamma-ray burst initiate the late Ordovician mass extinction?" by Melott, Lieberman, Laird, et al. (2004)

THANK YOU!

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