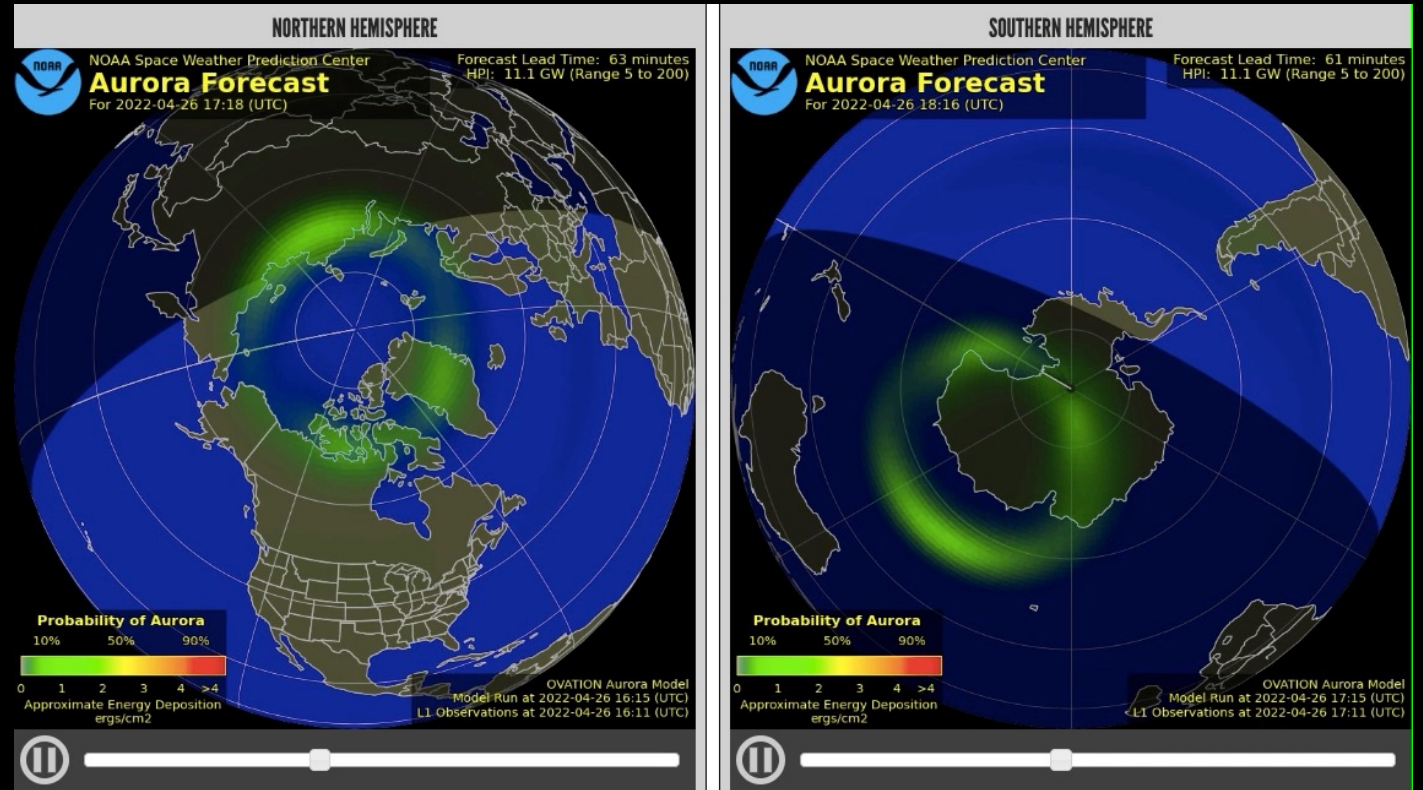


# Auroral ovals:

- Regions where the auroras typically occur
- Elliptical region around each geomagnetic pole, from  $\sim 56^\circ$  at midnight  $\sim 75^\circ$  at noon
- Becomes wider during geomagnetic storms and substorms



A short-term forecast of the location and intensity of the aurora  
Video credit: NOAA

# Aurora on Other Planets

You can find Auroras on Jupiter, Saturn, Uranus and Neptune



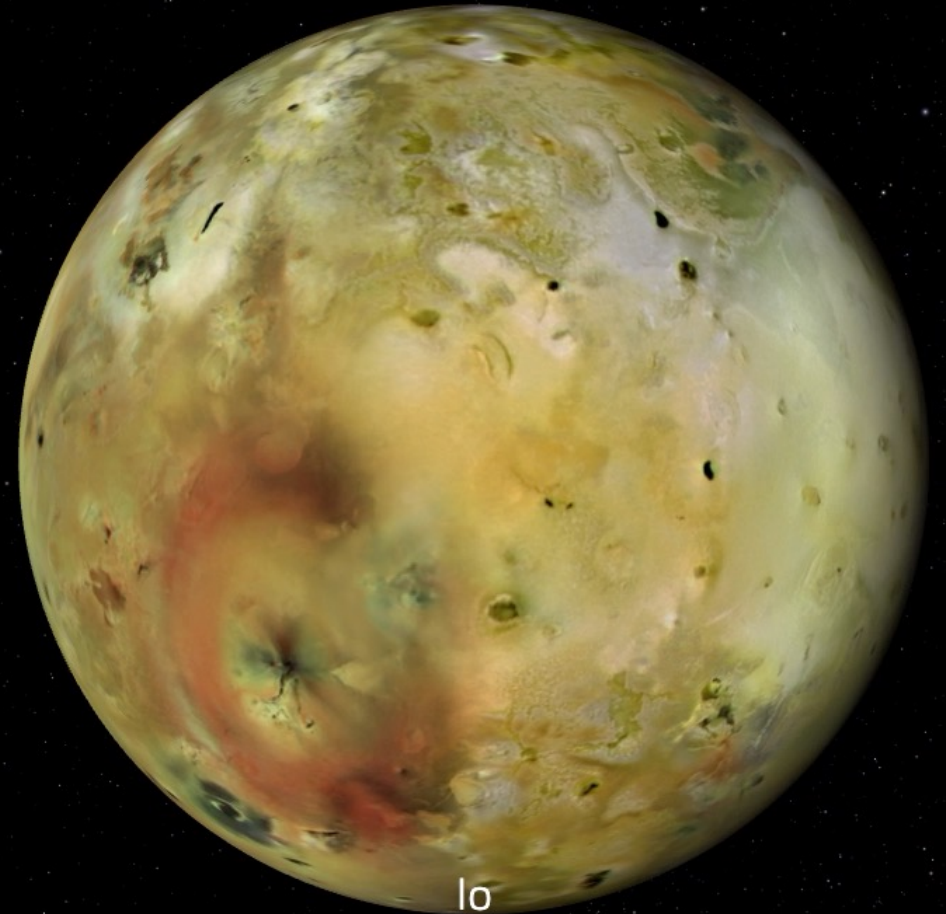
Jupiter's aurora observed by  
NASA's Hubble Space Telescope



Saturn's aurora observed by NASA's  
Hubble Space Telescope

# Jupiter's Auroras

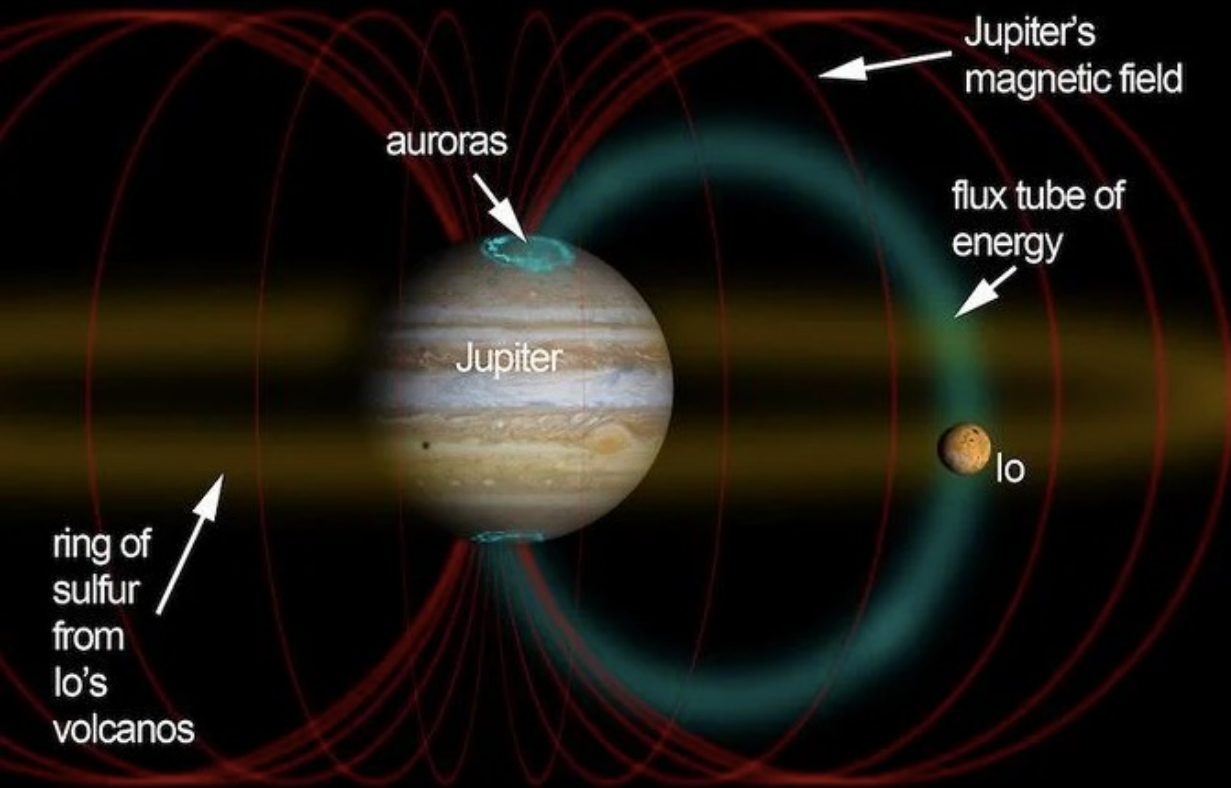
- Source of charged particles:  
Solar wind & the Jupiter's moon Io
- Io is the most volcanically active world in the Solar System, with hundreds of volcanoes, some erupting lava fountains dozens of kilometers high
- Jupiter has the most powerful auroras in the solar system
- Auroras on Earth may last for a few hours, but on Jupiter they never end



Io  
Major Moon\* | 1821.3 KM

Io: The Jupiter's moon  
Video credit: NASA

# Jupiter-Io coupling



- Io orbits within the Jupiter's intense magnetic field and constantly couples with Jupiter's magnetosphere
- Volcanic eruptions on Io eject large amounts of sulfur dioxide gas into space, forming a large torus around Jupiter
- Io plasma torus is the main source of plasma for the Jovian magnetosphere

A schematic showing the Jupiter, Io, Jovian magnetic field lines and Io plasma torus  
credit: Ron Miller

# An Example of A Stellar Aurora

- In 2019, Vedantham et al. found an unusual coincidence between a radio detection and the low-mass/red dwarf star **GJ1151**
- In 2020, J. Sebastian Pineda concluded that the radio emission from the star could only be induced by the presence of a **closely orbiting planet**
- The planet candidate around GJ1151 is expected to be linked to its host star through a magnetic flux tube, causing a **stellar aurora** at its foot

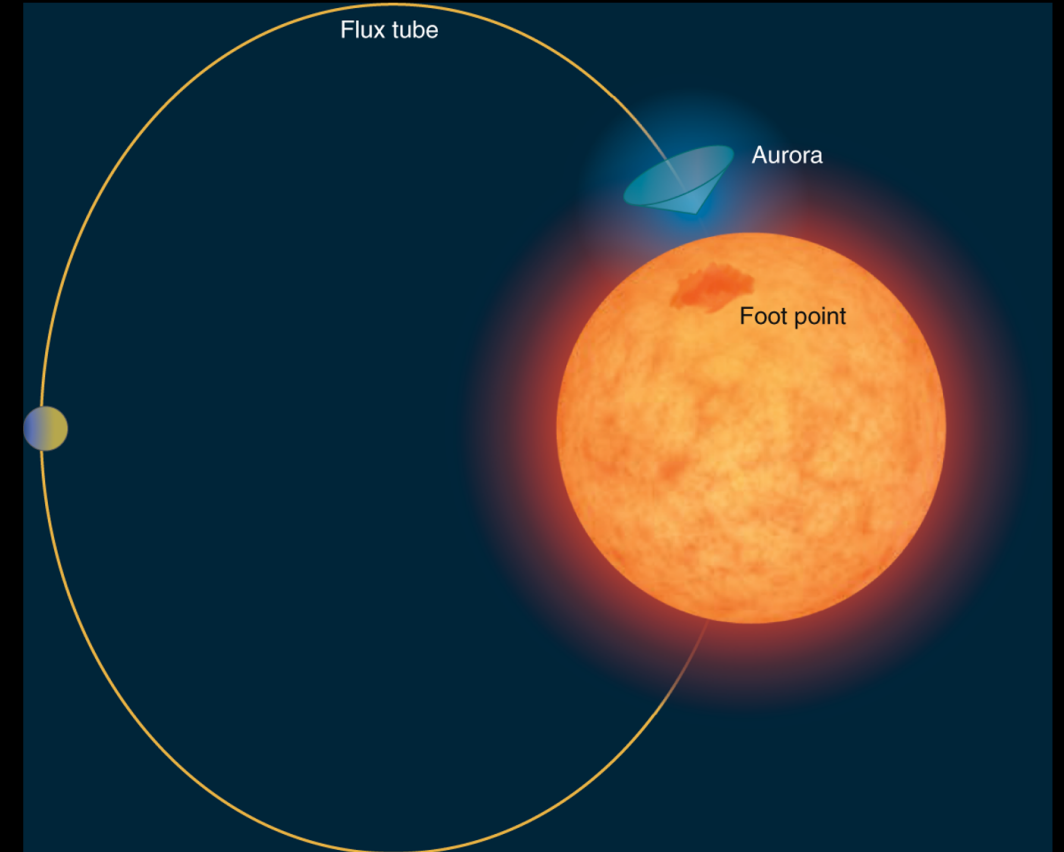


Illustration credit: J.S, Pineda 2020

# Space Hurricane

- In 2020, using satellite observations that had been made on 20 August 2014, researchers identified a **Space Hurricane** in the upper polar atmosphere (altitude ~ 110–860 km)
- The Space Hurricane had a cyclone-like auroral spot around the north magnetic pole
- Its diameter was over 1000 km with multiple arms and anti-clockwise rotation
- The hurricane lasted nearly 8 hours
- The space hurricane happened during very **low geomagnetic activity**. Therefore, there may be more space hurricanes to be discovered

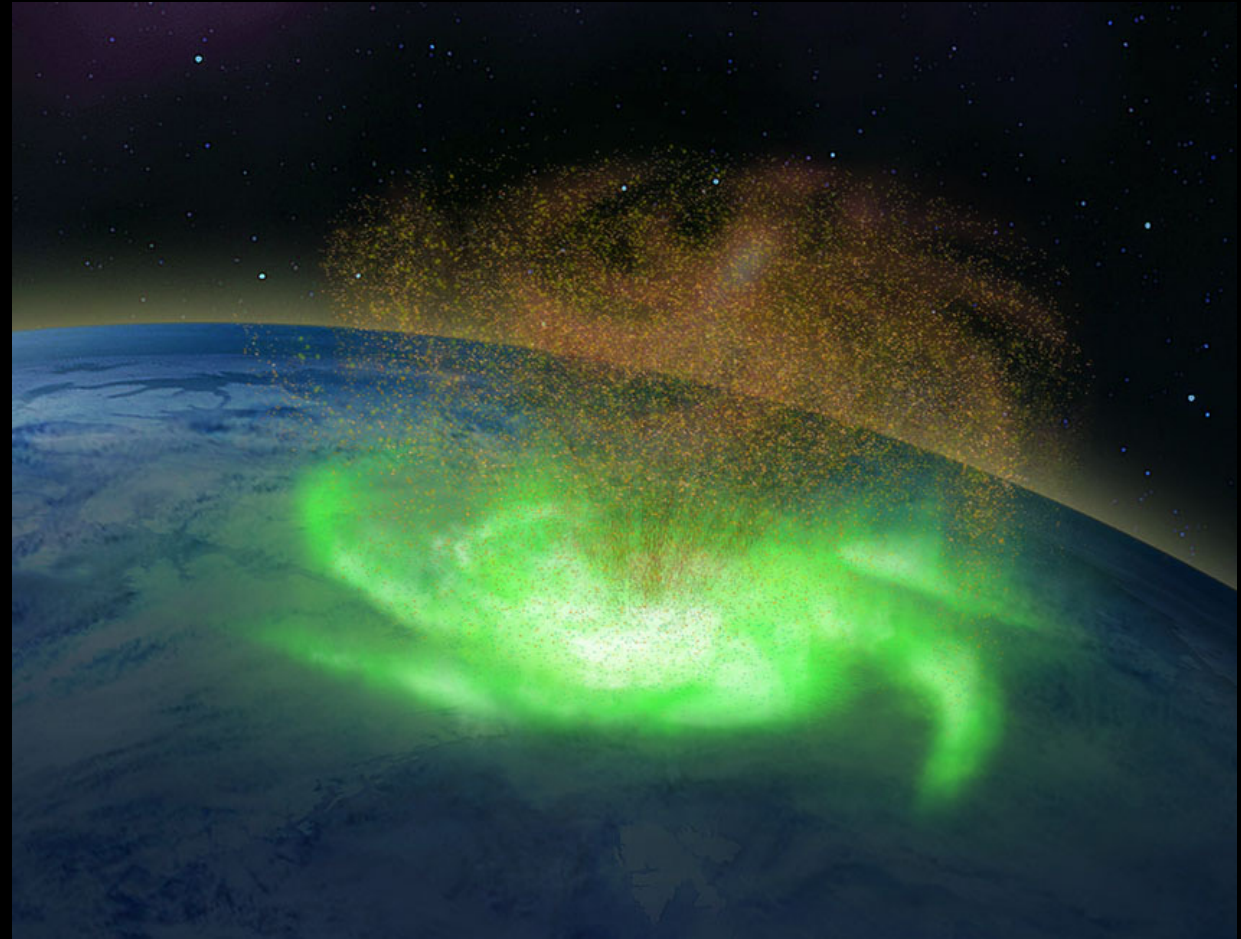
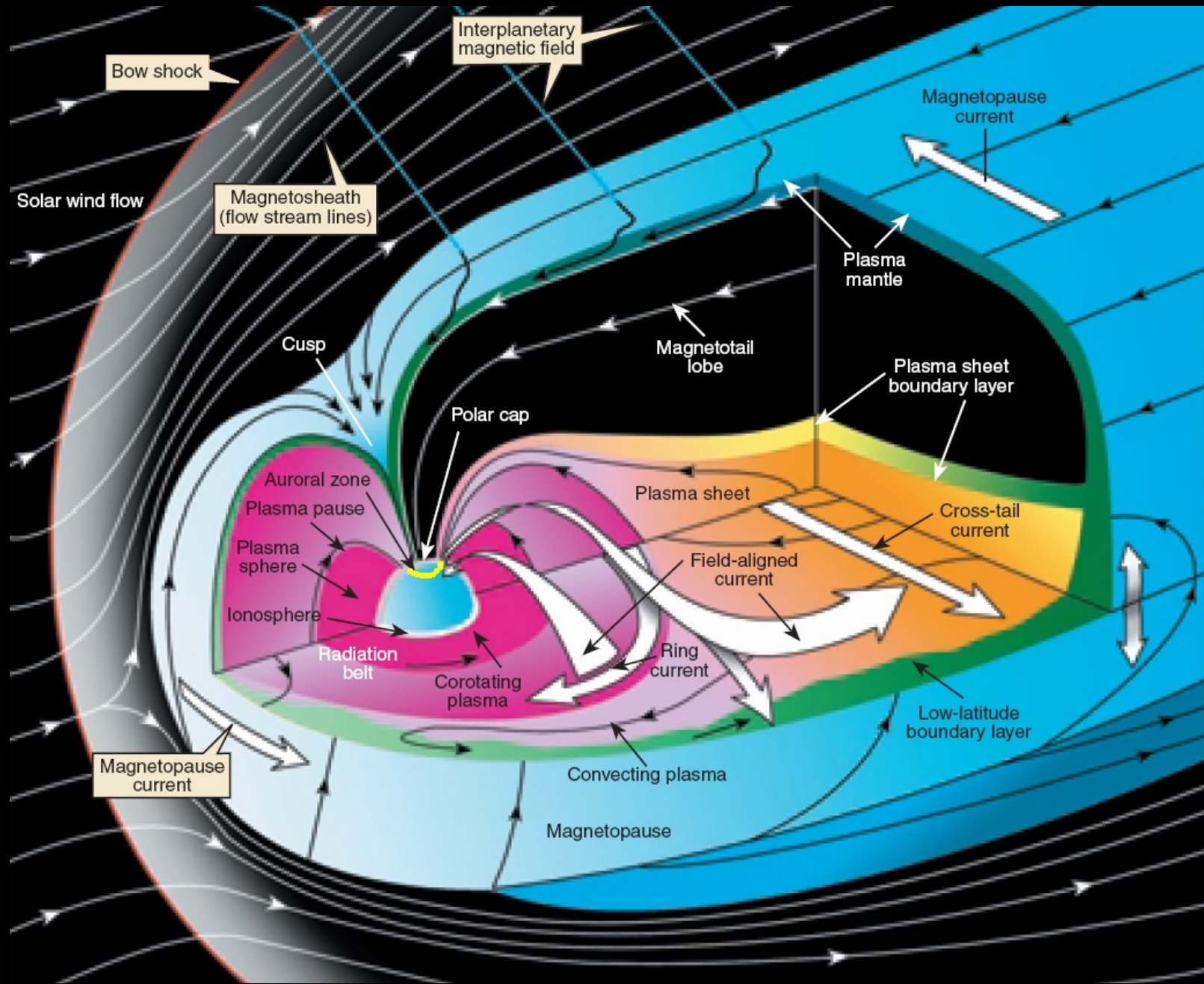


Illustration credit: space hurricane by Shandong University

# **Geomagnetic Data**

**Geomagnetic Indices**  
**Where to Find them**  
**How to Use them**



Earth's magnetosphere. Image credit: NASA



# Ring current

- The **Ring current** is located at  $\sim 3$  to  $8 R_{\oplus}$ , circulates clockwise (when viewed from the north )
- The current produces a B-field in opposition of  $B_{\oplus}$
- Dst index measures the intensity of the ring current
- Deviation of H (north-south) component of the magnetic field

$$R_{\oplus} = 6,371 \text{ (km)}$$

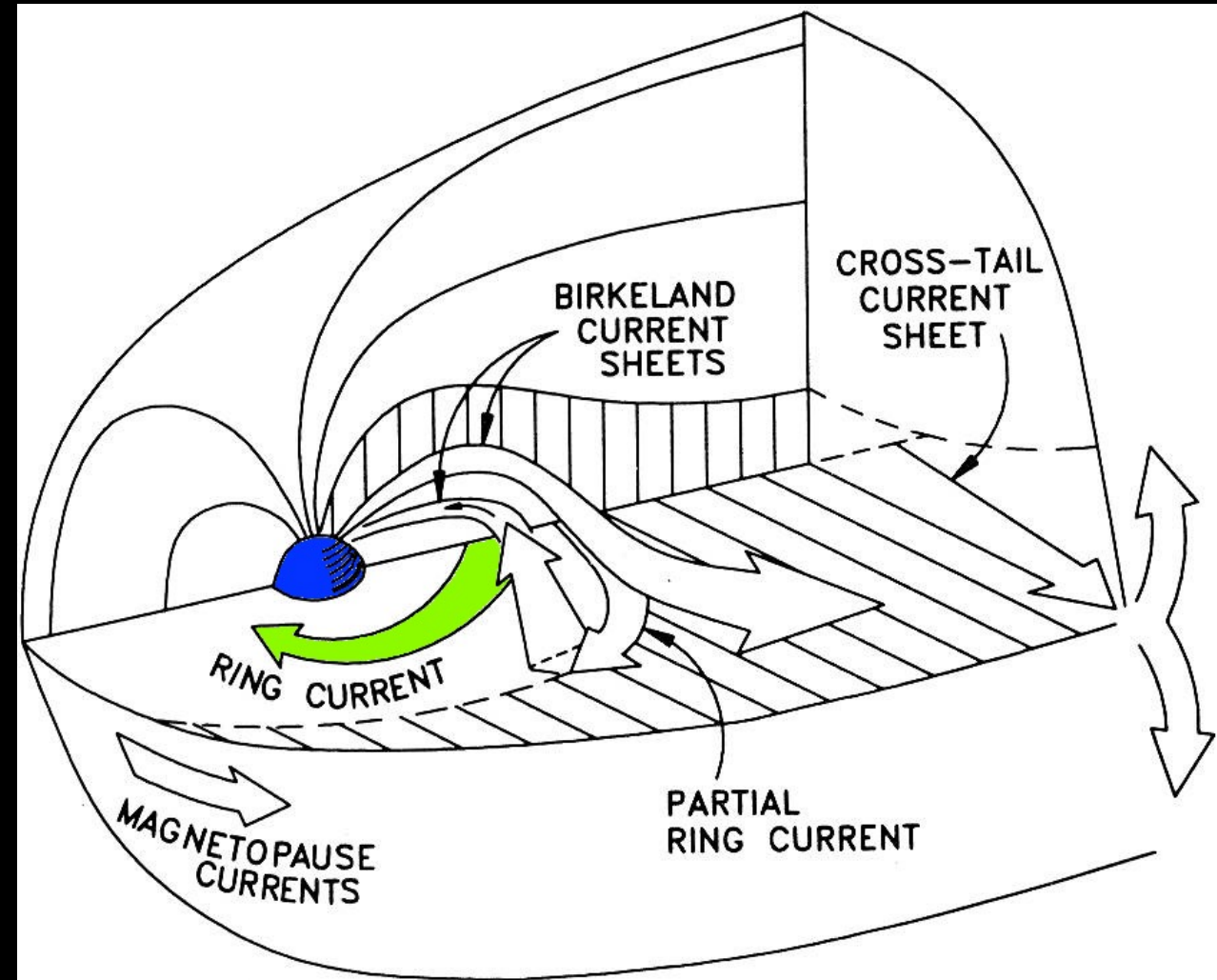
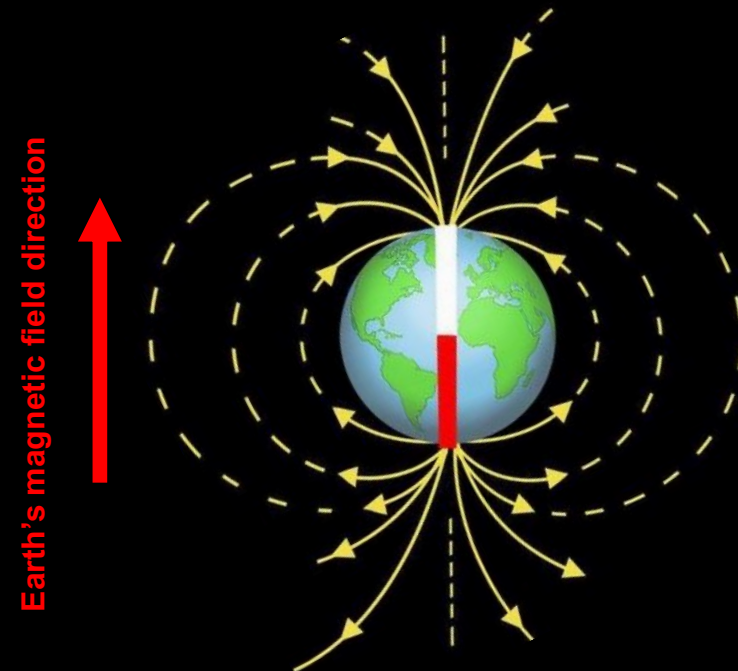
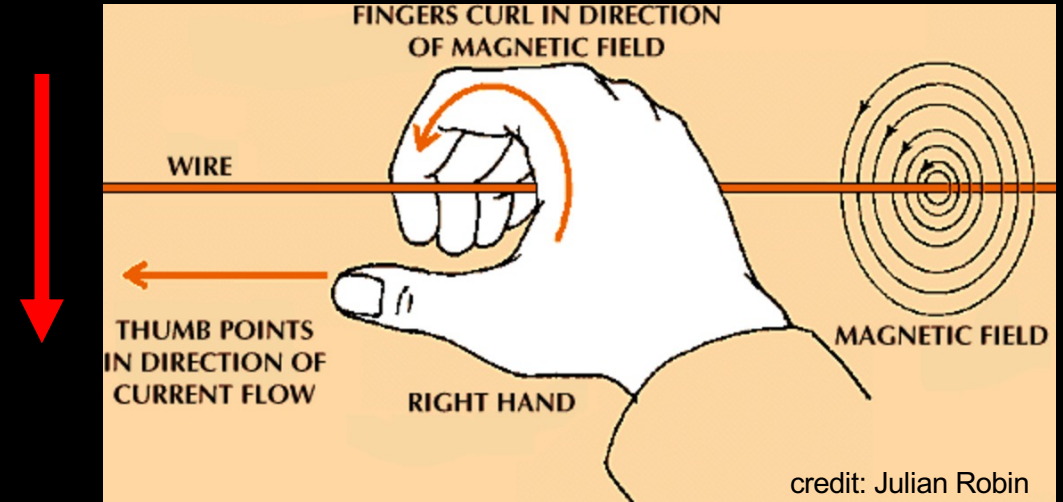


Illustration credit: David P. Stern

# How the Ring Current affects the Earth magnetic field

- Moving charge particles create an electric current  $I = \frac{q}{t}$
- An electric currents induce magnetic field as well



# Disturbance storm time (Dst) index

- A measure of the ring current strength
- Four stations near the magnetic equator
  - Magnetic equator: There is no vertical (Z) component to the magnetic field
  - The magnetic equator is not fixed, but slowly changes

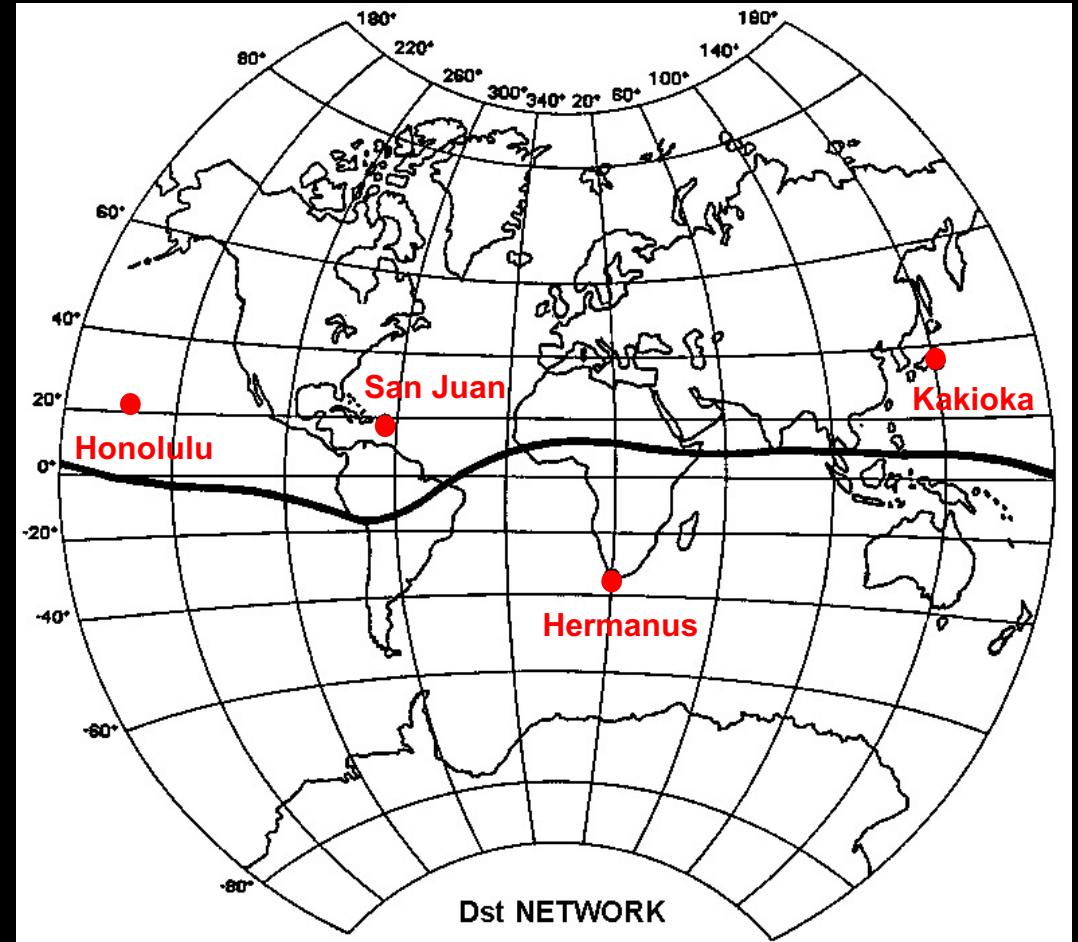


Illustration credit: World Data Center for Geomagnetism



WDC for Geomagnetism, Kyoto  
Hourly Equatorial Dst Values (FINAL)  
MARCH 2015

DAY	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	-34	-44	-30	-31	-28	-42	-55	-53	-56	-51	-50	-47	-46	-41	-36	-32	-29	-26	-22	-21	-22	-21	-27	-26
2	-21	-20	-30	-35	-30	-42	-43	-53	-64	-62	-54	-50	-53	-53	-49	-49	-41	-40	-36	-29	-27	-27	-25	-23
3	-24	-22	-28	-26	-25	-26	-27	-26	-22	-26	-28	-27	-25	-27	-27	-27	-25	-25	-28	-21	-21	-23	-27	-31
4	-27	-18	-16	-17	-15	-13	-11	-8	-4	-5	-6	-7	-11	-15	-16	-19	-20	-20	-17	-14	-15	-11	-14	-18
5	-15	-11	-9	-9	-7	-5	-4	-3	-3	-6	-8	-7	-12	-19	-13	-14	-15	-12	-10	-10	-8	-7	-3	-3
6	-3	0	2	6	3	-5	-14	-30	-30	-20	-17	-14	-16	-16	-14	-12	-11	-8	-8	-9	-14	-17	-9	-6
7	-8	-11	-12	-17	-20	-27	-27	-25	-19	-20	-24	-22	-19	-12	-11	-12	-10	-14	-14	-16	-20	-24	-24	-20
8	-17	-13	-13	-14	-15	-12	-7	-7	-9	-8	-12	-18	-21	-18	-21	-19	-17	-20	-21	-18	-15	-14	-13	-15
9	-18	-23	-21	-22	-19	-16	-17	-18	-17	-16	-14	-11	-9	-9	-10	-9	-10	-10	-5	-4	-4	-4	-4	-3
10	-1	-4	-4	-6	-6	-4	-2	-1	1	-3	-7	-3	-5	-6	-6	-7	-7	-6	-6	-8	-6	-4	-4	-5
11	-6	-6	-6	-6	-5	5	6	8	0	2	1	2	-6	-11	-14	-14	-12	-12	-15	-20	-19	-16	-15	-14
12	-15	-12	-8	-10	-11	-7	-12	-22	-24	-23	-19	-19	-15	-17	-18	-13	-9	-9	-9	-8	-8	-11	-13	-15
13	-13	-12	-9	-3	-2	1	0	0	-1	-2	0	0	-3	-16	-20	-11	-7	-10	-15	-15	-11	-10	-7	-10
14	-12	-11	-12	-13	-14	-15	-12	-9	-8	-7	-5	-4	-4	-4	1	3	4	2	3	2	-1	-3	-5	-11
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17	4	3	3	2	13	45	25	-18	-54	-83	-75	-54	-55	-75	-93	-118	-143	-162	-154	-177	-182	-198	-234	-225
18	-200	-189	-172	-155	-148	-136	-133	-124	-123	-117	-111	-99	-97	-91	-88	-91	-86	-82	-88	-94	-95	-94	-94	-93
19	-99	-94	-88	-81	-88	-84	-81	-73	-71	-78	-73	-78	-77	-83	-84	-80	-73	-72	-71	-70	-71	-83	-83	-70
20	-75	-81	-74	-69	-65	-64	-71	-68	-63	-61	-62	-65	-58	-57	-55	-56	-62	-66	-64	-60	-59	-56	-56	-65

# Database for the Geomagnetic indices

- Dst index
- AL/AU or AE index
- Kp index

## World Data Center for Geomagnetism

- <https://wdc.kugi.kyoto-u.ac.jp/wdc/Sec3.html>

- Check Dst index and try to find a Geomagnetic Storm

World Data Center for Geomagnetism, Kyoto  
Our website is now always-on SSL; http access will be redirected to https.  
<http://wdc.kugi.kyoto-u.ac.jp/> --> <https://wdc.kugi.kyoto-u.ac.jp/> (April 1, 2022)

operated by  
Data Analysis Center for Geomagnetism and Space Magnetism  
Graduate School of Science, Kyoto University  
Kitashirakawa-Oiwake Cho, Sakyo-ku  
Kyoto 606-8502, JAPAN

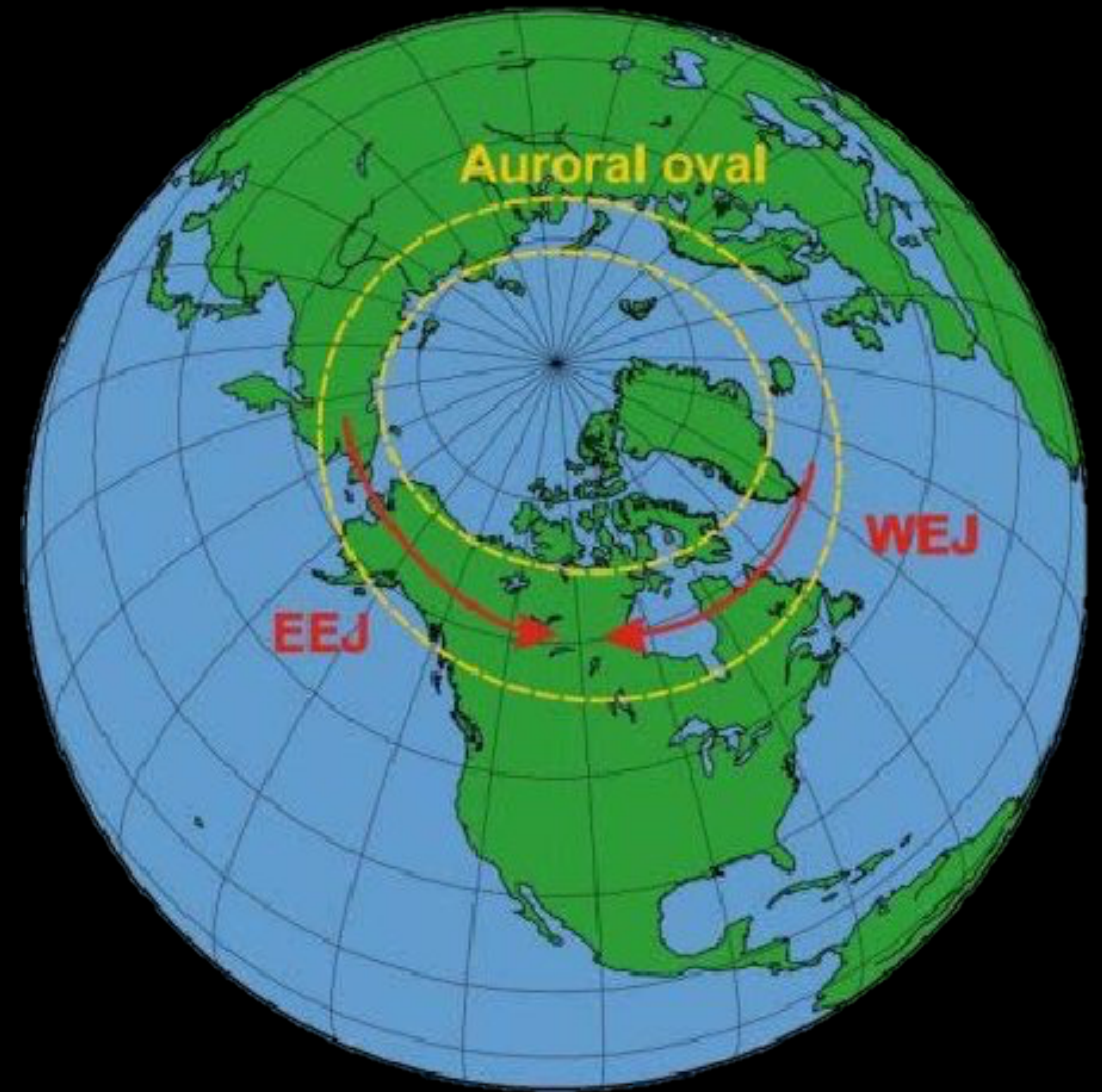
TEL: +81-75-753-3929 (075-753-3929, inside Japan)  
FAX: +81-75-722-7884 (075-722-7884, inside Japan)

Home Page | WDC for Geomag, Kyoto | E's magnetic field? | Data Service | I-Magnet | Link

- 1. World Data Center for Geomagnetism, Kyoto**  
Data Analysis Center for Geomagnetism and Space Magnetism,  
Research, Publication list, Staff, Access Guide and Map, WDC system and others
- 2. What is the Earth's magnetic field?**  
Magnetic north, geomagnetic and magnetic pole, Geomagnetic elements,  
Geomagnetic field observation and collection of the data (Geomagnetic observatories on the Google Earth),  
International Geomagnetic Reference field and others
- 3. Geomagnetic Data Service**  
Indices, Geomagnetic Field Data at the Observatories, Models, Data Catalogue and others
- 4. INTERMAGNET Kyoto GIN Home Page**  
QL monitor of INTERMAGNET data, about INTERMAGNET and others
- 5. Link to other sites**  
Kyoto University, ICSU/WDS's, Geomagnetic Observatories, Societies and others

# Equatorial and Auroral Electrojets

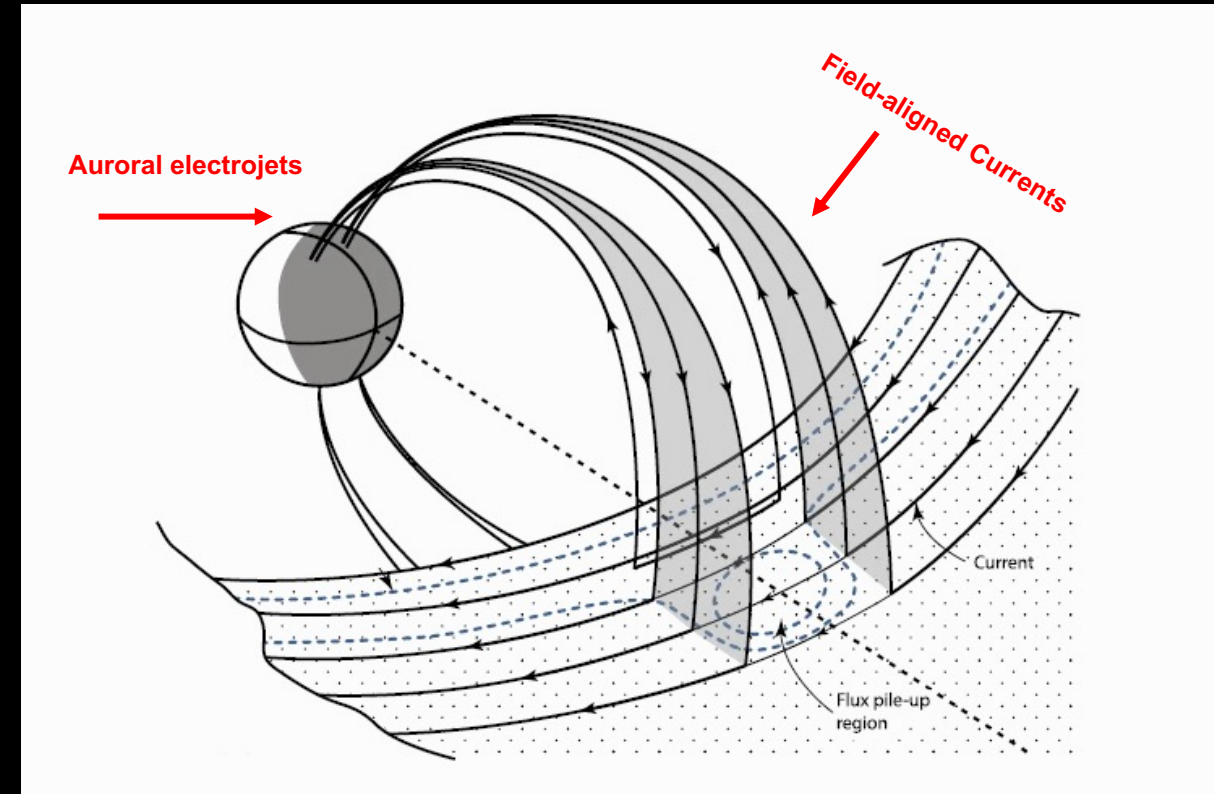
- An electrojet is an electric current which travel around the Earth's ionosphere
- There are two electrojets: Above the magnetic equator (the equatorial electrojet), and near the Northern and Southern Polar circles (the Auroral electrojets)



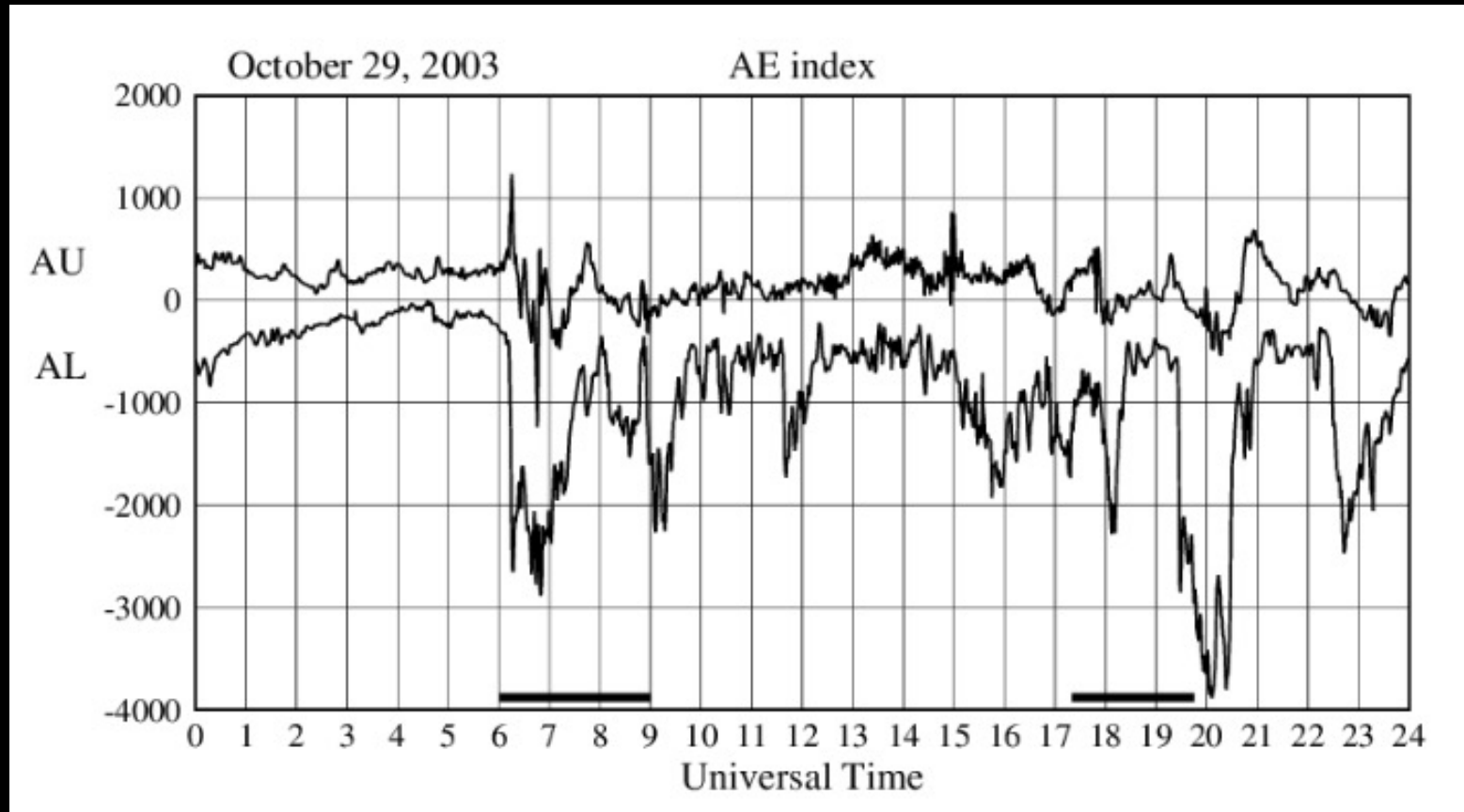
Representation of the East (EEJ) and West (WEJ) auroral electrojet  
Image credit: Piccinelli et al. 2014

# Auroral Electrojet (AE) index

- AE is designed to provide a global, quantitative measure of auroral zone magnetic activity
- Produced by Auroral Electrojets flowing below and within the auroral oval
- Derived from variations in the horizontal component observed at selected (10-13) observatories



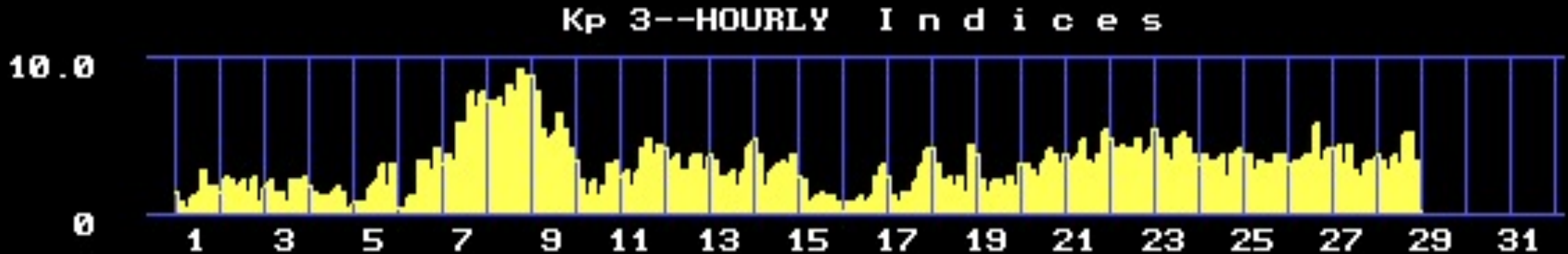
Auroral electrojets  
credit: L. Kepko. et al



- AU and AL indices are respectively the largest and the smallest values in the horizontal component
- The difference,  $AU$  minus  $AL$ , defines the AE index



# Geomagnetic Kp index



- The  $K_p$  is used to characterize the magnitude of Geomagnetic Storms, or quantifies disturbances in the horizontal component of earth's magnetic field
- 3-hourly range index, 13 geomagnetic observatories (ranging from  $44^\circ$  to  $60^\circ$  northern or southern geomagnetic latitude)
- Scaled from 0 to 9, expressed in thirds of a unit, e.g. 5- is  $4\frac{2}{3}$ , 5 is 5, 5+ is  $\frac{1}{3}$


# All sky camera

Longyearbyen all-sky camera

National Institute of Polar Research



ScreenCast-O-Matic.com

2013/03/02  
18:50'10" 

- Used in meteorology, astronomy and visual observation of auroras
- Capture a photograph of the entire sky
- All-sky cameras that are used for imaging auroras have special optical elements such as fish-eye lenses or spherical mirrors to acquire an image of the whole sky in one shot

# All sky camera data



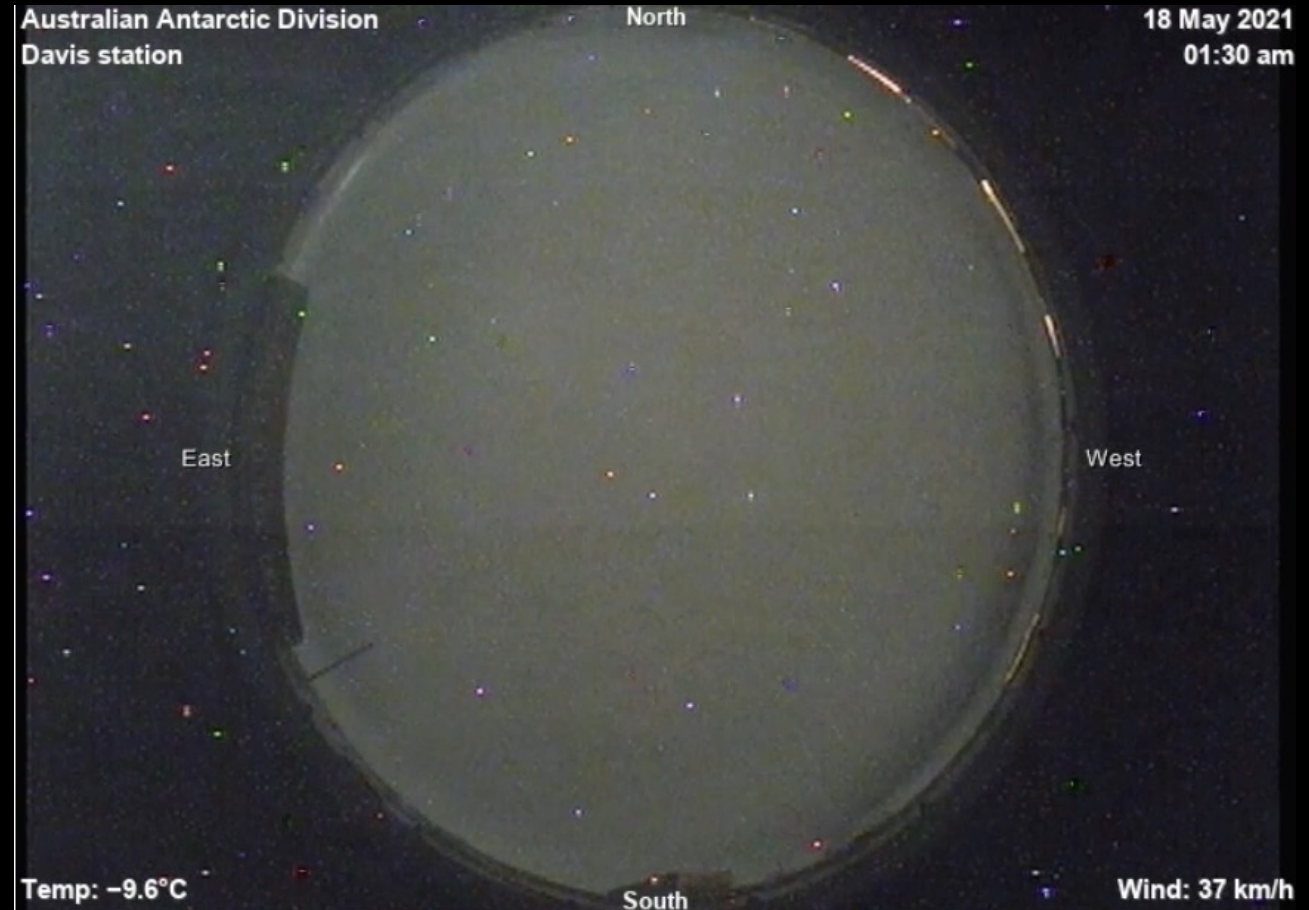
Oct. 27, 2010

Photo Credit: Terence Murtagh & Nicholas  
Cades Observatory, Kingston, TAS, Australia  
Holdsworth

- Sodankylä Geophysical Observatory  
<http://www.sgo.fi/Data/RealTime/allsky.php>
- Skibotn Observatory, Norway:  
<https://fox.phys.uit.no/ASC/ASC01.html>
- Kiruna station, Sweden:  
[https://www2.irf.se/Observatory/?link=All-sky\\_sp\\_camera](https://www2.irf.se/Observatory/?link=All-sky_sp_camera)
- Syowa (or Showa) station, South Pole:  
<http://polaris.nipr.ac.jp/~acaaurora/aurora/Syowa/> **Not working!**

# Davis Station Sky-cam

- Davis station is one of the permanent research center in Antarctica
- Operated by Australian Antarctic Division
- Coordinates:  $68^{\circ} 34' 36''$  S,  $77^{\circ} 58' 3''$  E
- Sky-cam produces images of the full sky and provides a view for the study of Antarctic clouds with similar sensitivity to the naked eye
- <https://www.antarctica.gov.au/antarctic-operations/webcams/davis/>



Sky-cam at the Davis station  
Video credit: Australian Antarctic Division

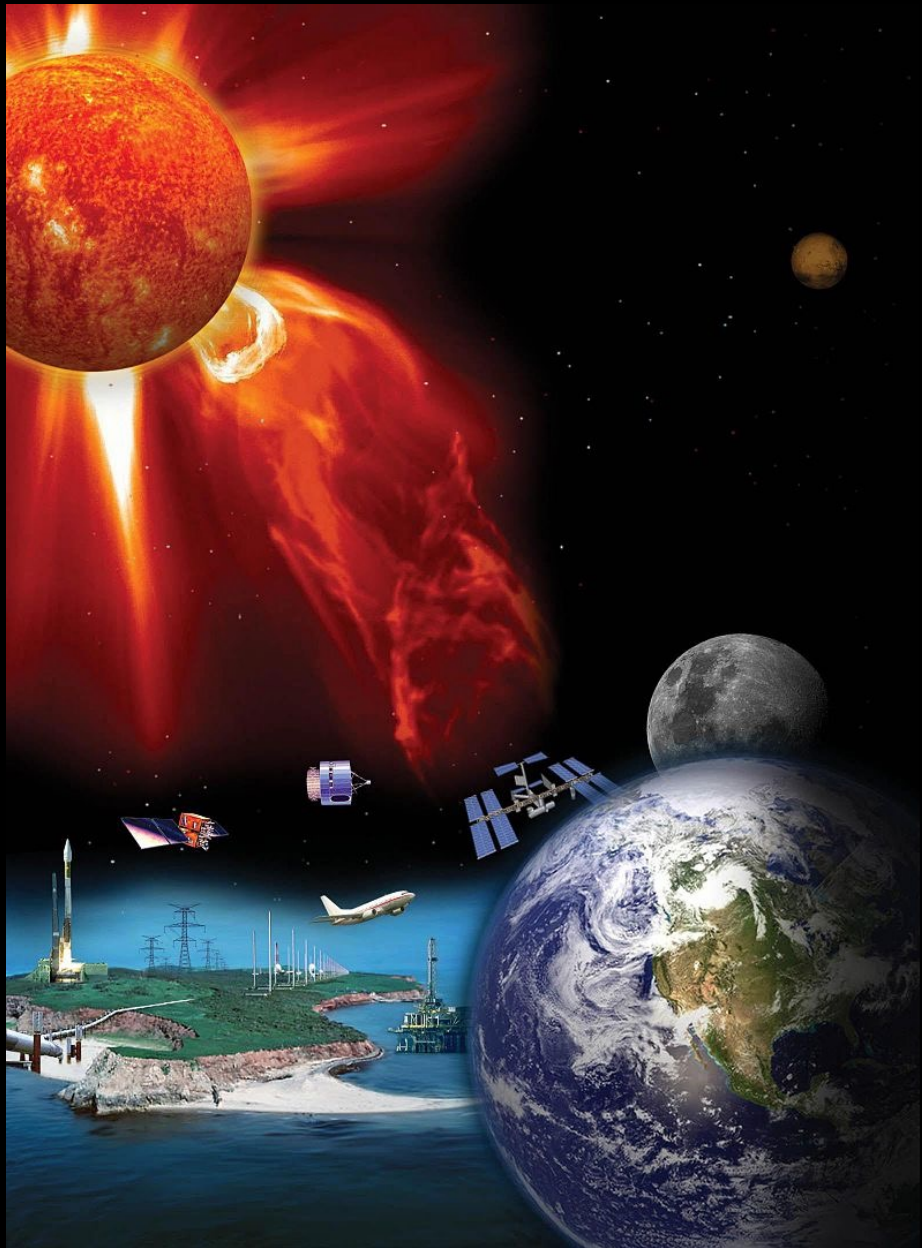
# **Space Weather impacts**

**Extreme Geomagnetic Storms**

**Future Missions**

# Space Weather Impacts

- GPS systems
  - The charged plasma of the ionosphere bends the path of the GPS radio signal
- Satellite communications
  - Radio signals propagating to and from a satellite in orbit are affected by ionosphere condition
- Satellite Drag
  - Especially for satellite in low Earth orbit (LEO)
  - International Space Station & Hubble telescopes operate in LEO




credit: NASA

# Geomagnetically Induced Current (GIC)


- Quick changes in the Earth's magnetic field create GICs through electromagnetic induction and cause GIC to flow in power grids, pipelines, and railway systems
- Most GICs are triggered by CMEs
- GIC have become one of the main space weather concerns, and the potential threat in operating high-voltage power transmission systems

National Aeronautics and Space Administration

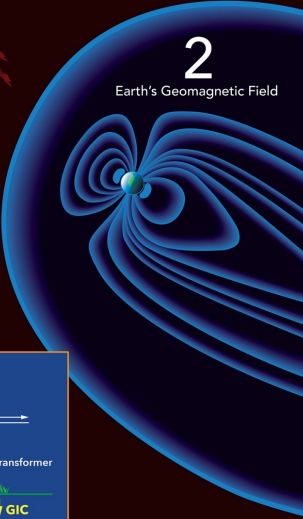


## GEOMAGNETICALLY INDUCED CURRENTS

**1**  
Coronal Mass Ejection (CME)

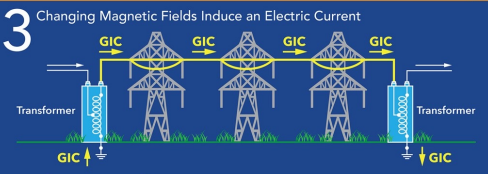


**2**  
Earth's Geomagnetic Field



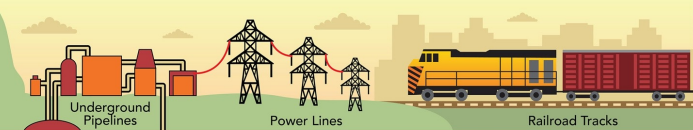
Geomagnetically Induced Currents (GICs) can result from geomagnetic storms—a type of space weather event in which Earth's magnetic field is rattled by incoming magnetic solar material. Most GICs are triggered by coronal mass ejections (1), or CMEs, which interact with the magnetic field around Earth (2) and cause it to rattle. The quick-changing magnetic fields create GICs through a process called electromagnetic induction (3). GICs can flow through railroad tracks, underground pipelines, and power grids. In extreme cases, they can cause blackouts.

**3** Changing Magnetic Fields Induce an Electric Current



**WHAT IS THE IMPACT?**  
Though widespread permanent damage to power systems is unlikely, extreme storms can cause blackouts over extended areas. That's why NASA and other federal agencies work with the power and insurance industries to develop plans and standards for dealing with GICs.

**GICs CAN RUN THROUGH ANY LONG METAL STRUCTURE**



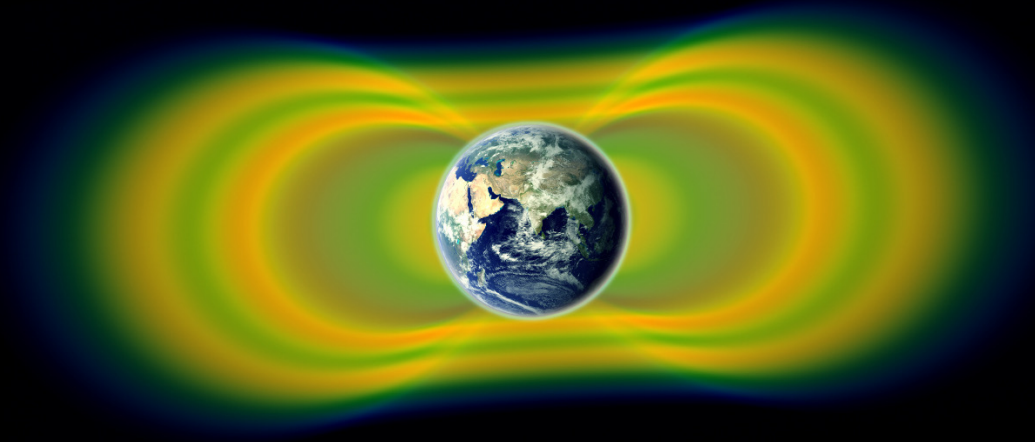
Underground Pipelines    Power Lines    Railroad Tracks

www.nasa.gov

credit: NASA

# Ahead of Webb Launch, NASA was Watching the Space Weather

- James Webb Space Telescope (JWST) estimated cost ~ 10 billion USD
- **Kp index:** avoid launching when the Kp index is 4 or higher, to avoid risks of losing communication with the spacecraft in the critical moments after launch
- **Van Allen belts:** One of the biggest threats to spacecraft after launch are the Van Allen radiation belts. So it is important to monitor the Belts, ensuring it stays within acceptable levels for launch

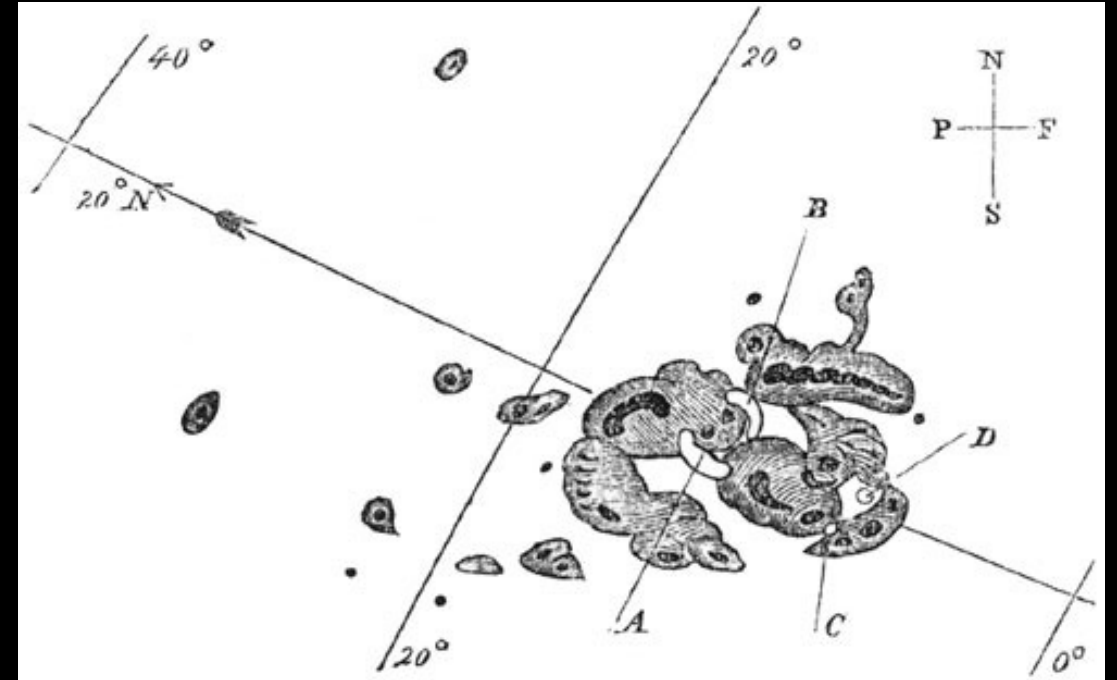


Van Allen radiation belts  
credit: NASA



# 1. Carrington Event

- September 1859, cycle 10
- Major CME arrived in ~18 hours
- Caused Global telegraph lines to spark
- Northern lights were observed as far south as Cuba, Hawaii and Tahiti
- Estimated total economic impact on modern technology : \$2 trillion (National Academy of Science)



Sunspot of September 1, 1859 as sketched by Richard Carrington

# 2. Quebec Blackout

- March 13, 1989
- Caused a 12-hour blackout in Quebec
- Kept the Montreal metro shut and closed the Doral Airport
- Caused a malfunction of the Space shuttle Discovery
- Auroras could be seen as far south as Florida and Cuba



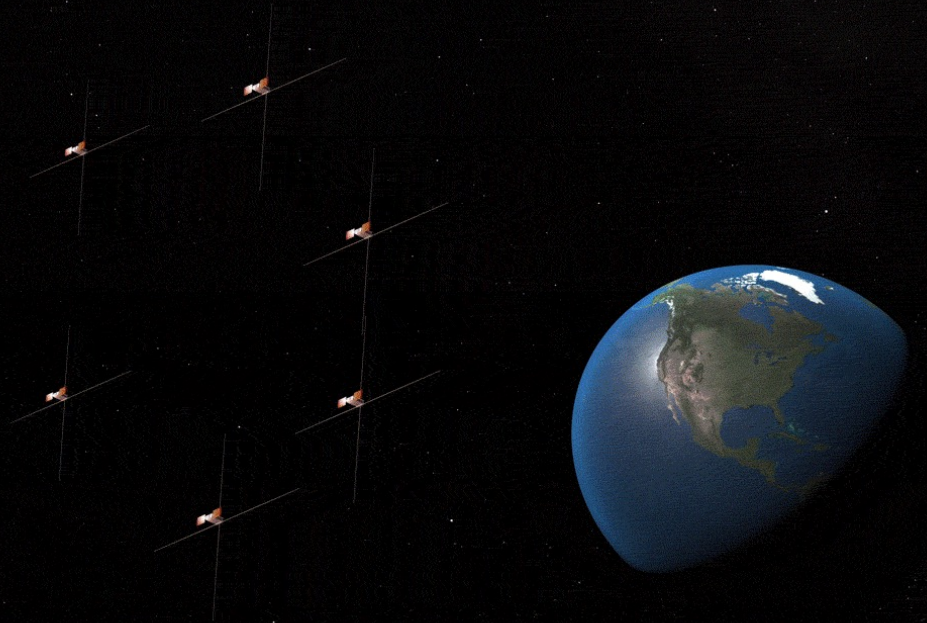
# 3. Halloween Geomagnetic Storm

- October 19 to November 7 - 2003
- Cycle 23, 2-3 years after solar maximum
- 17 major flares
- Solar & Heliospheric Observatory (SOHO) satellite failed temporary
- Auroras could be seen in Texas & Florida



# Sun Radio Interferometer Space Experiment (SunRISE)

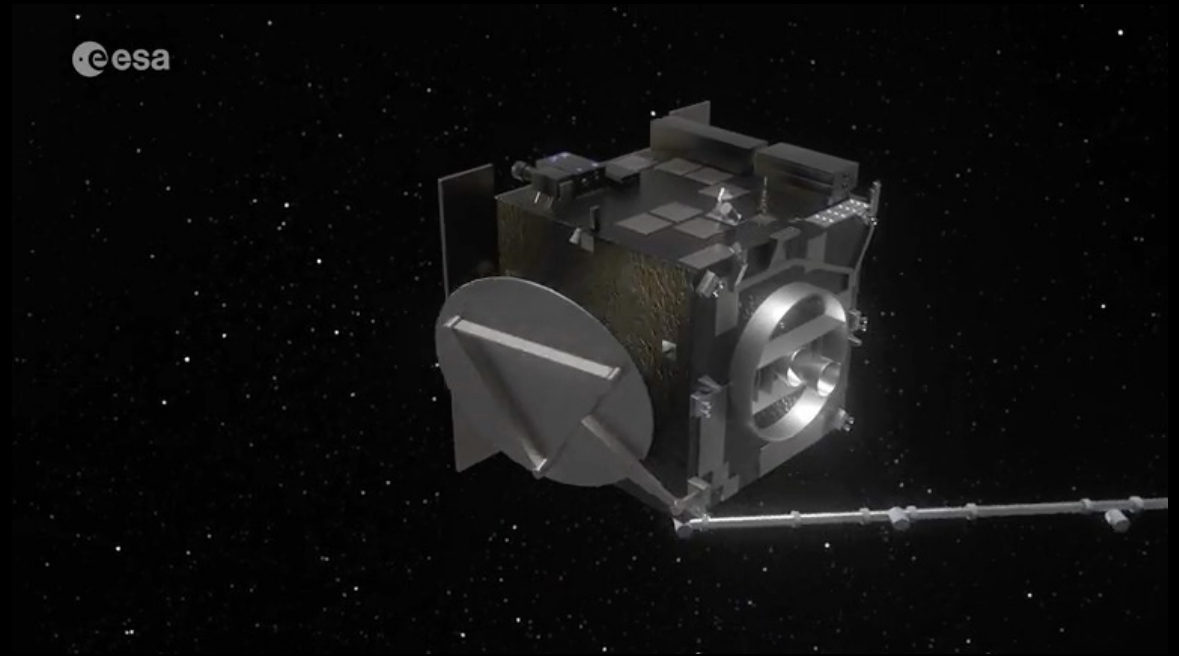
- An array of six CubeSats orbiting Earth at an altitude of 35,000 km
- SunRISE will orbit within 10 kilometers of one another well above Earth's atmosphere
- The constellation of small spacecraft uses interferometry, in which many smaller radio telescopes can be combined to mimic a single, much larger observatory with a very high resolving power
- SunRISE will create detailed 3D maps of where energetic radio emissions occur in the Sun



Animation credit: NASA

# ESA Vigil

- Vigil Will be launched in mid 2020s
- Monitoring space weather from L5 (400,000 km from Earth)
- L5 is an ideal location for monitoring for solar events such as CMEs from the side of the Sun
- We will be able to monitor, nowcast and forecast potentially dangerous solar events
- Vigil will give us time to protect at risk infrastructure on Earth, or life in space



Video credit: Esa