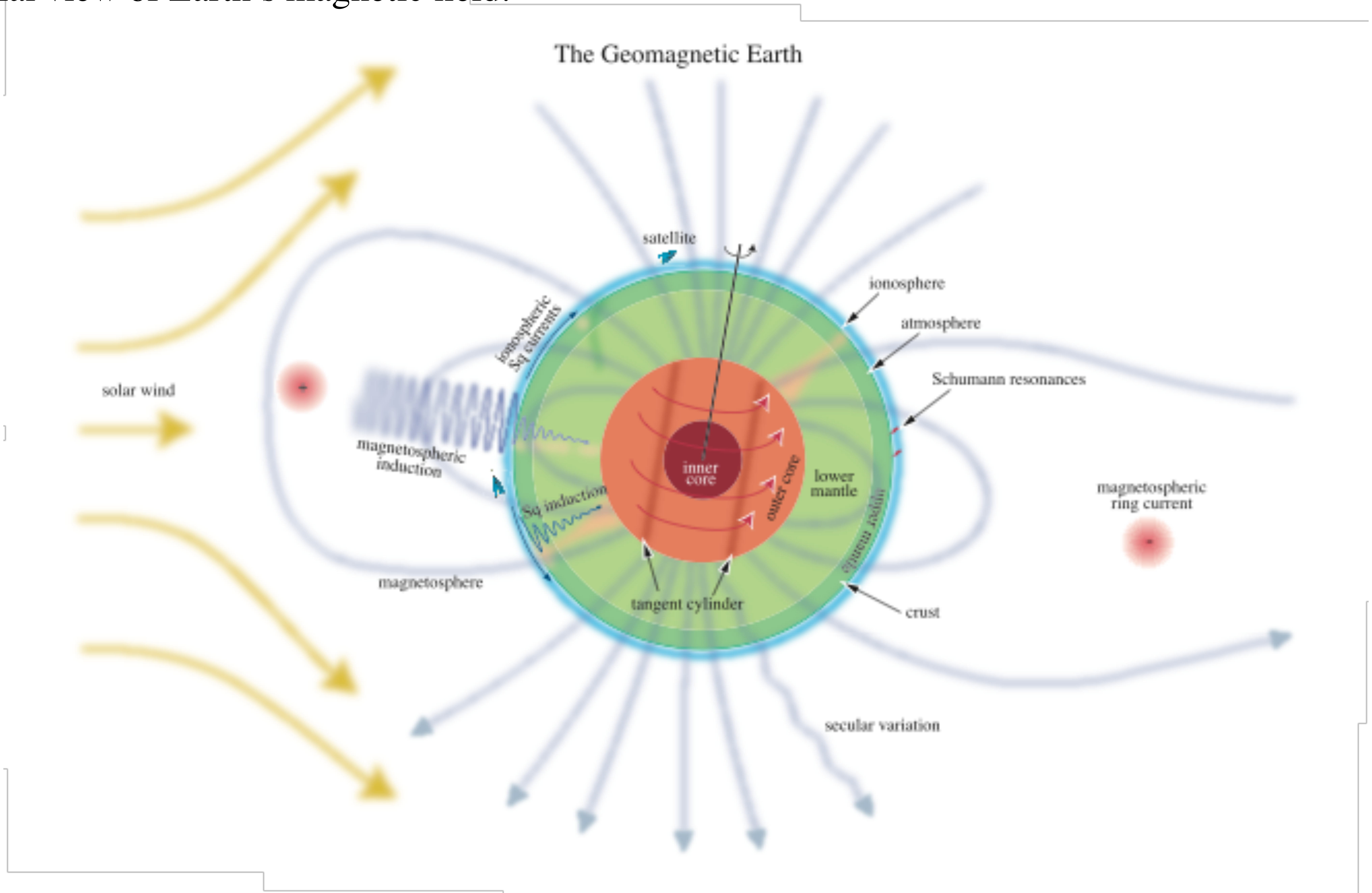
SIOG 231
GEOMAGNETISM AND ELECTROMAGNETISM

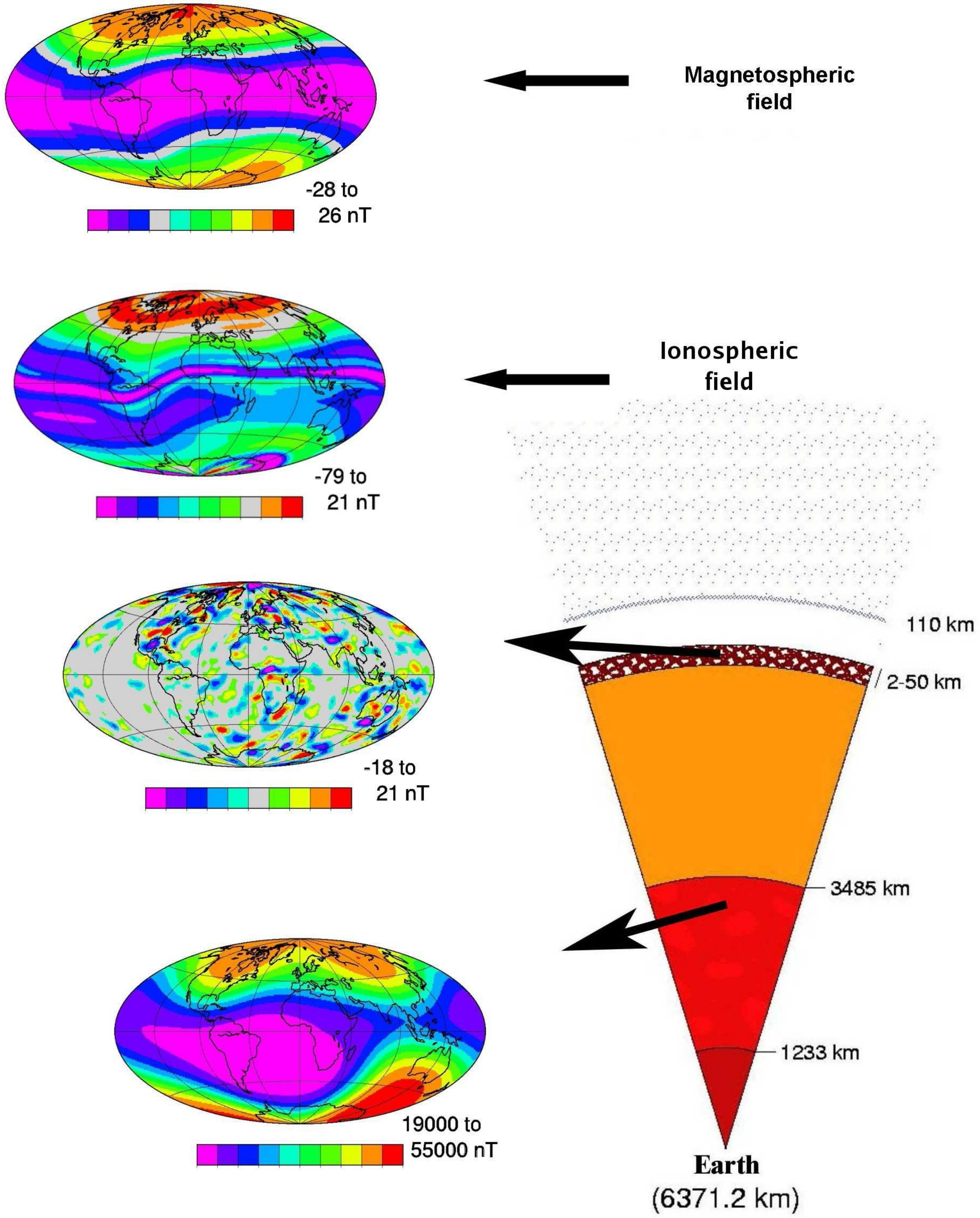
Lecture 8

Earth's Electromagnetic Environment

2/1/2024

A pictorial view of Earth's magnetic field:





Magnetic fields everywhere!

Ring current in magnetosphere

Ionospheric Sq currents and equatorial electrojet

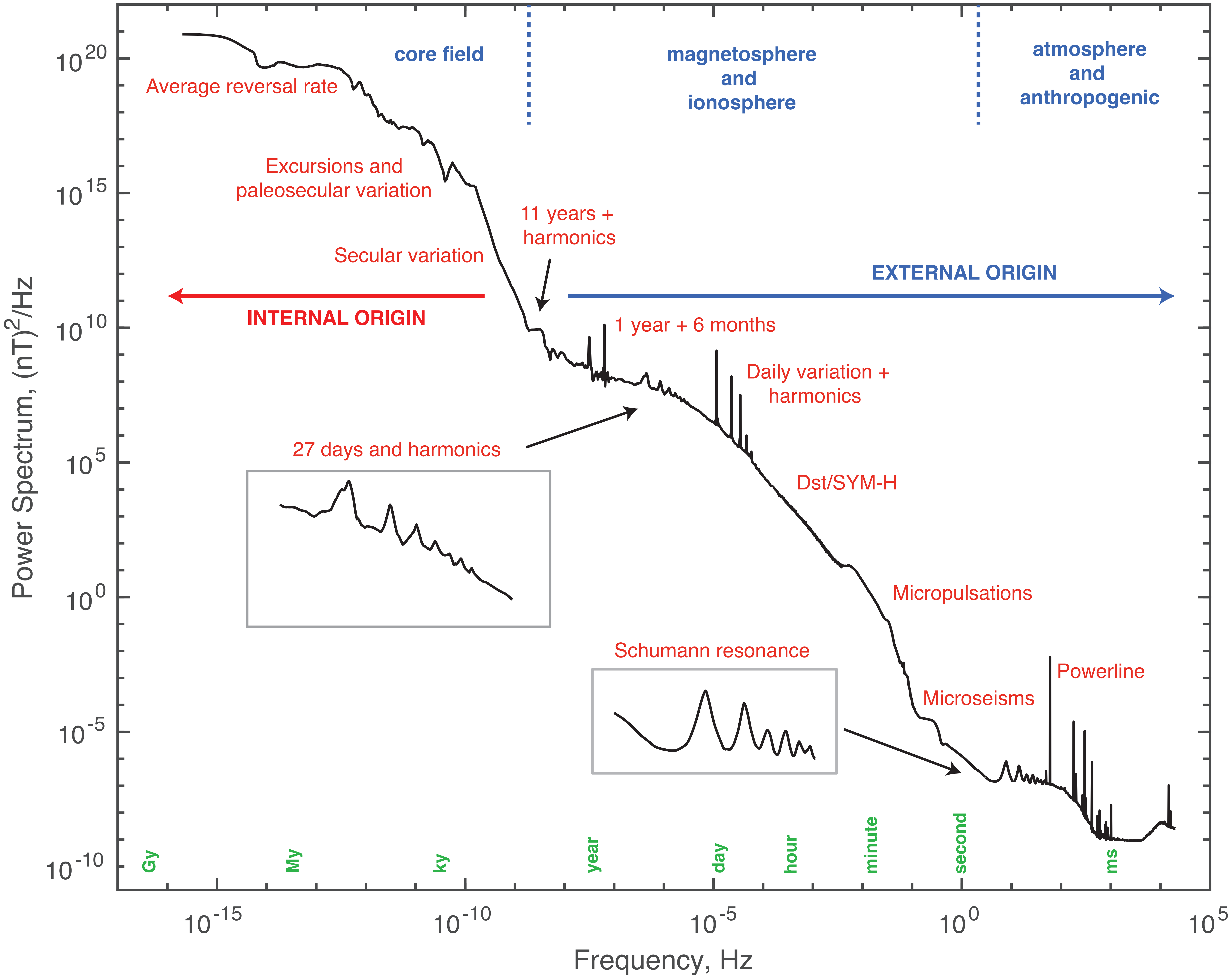
Lithospheric fields

Main field

As reconstructed from satellite data

(Mandea & Purucker, 2005)

The Grand Spectrum of the Geomagnetic Field



Earth's magnetic field varies on **all** time scales.

At periods > 11 years we can observe variations associate with the core geodynamo.

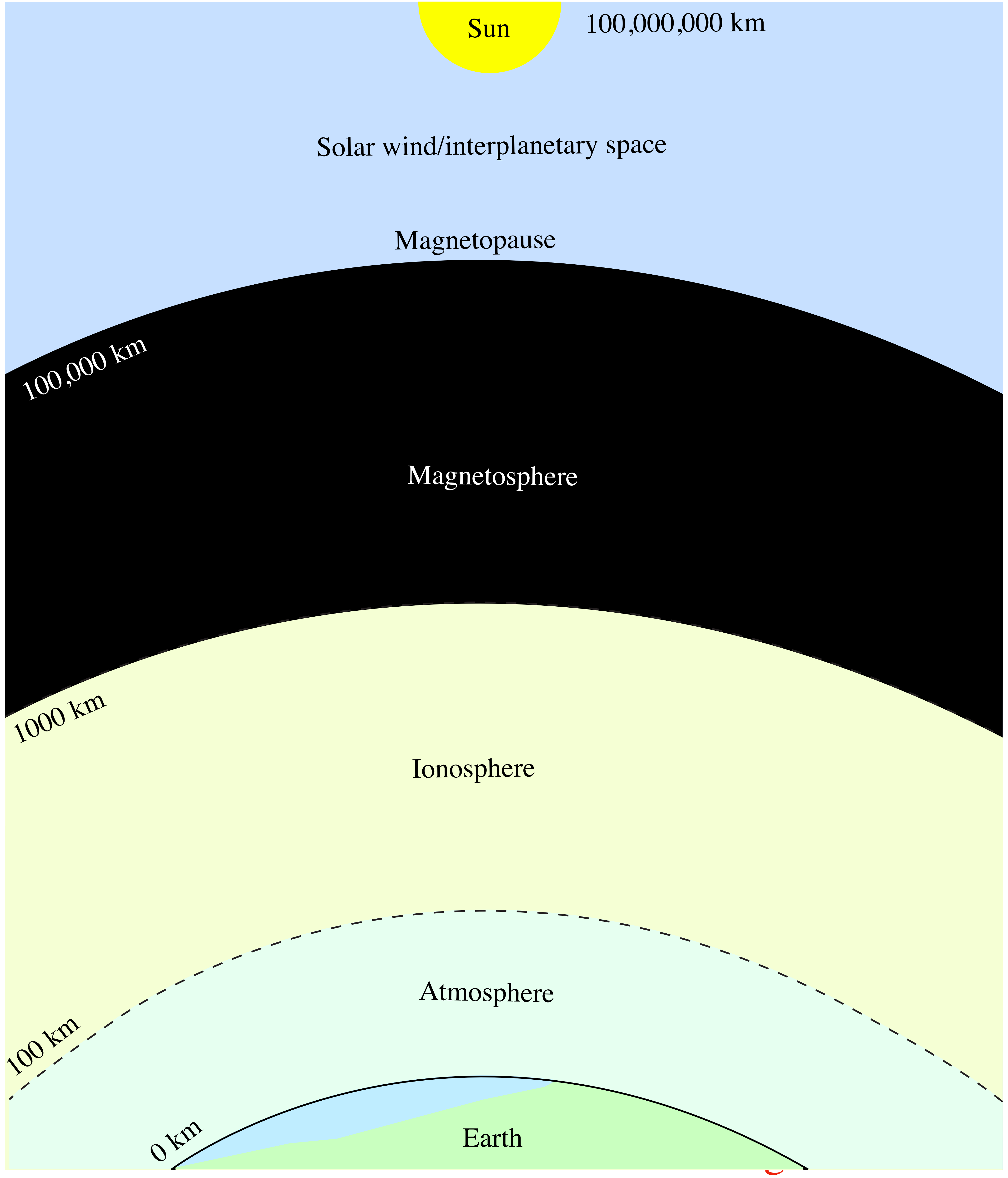
At periods < 11 years we can observe external magnetic field variations.

Electromagnetic induction driven by external field variations are used to probe electrical conductivity of the crust and mantle, typically to less than 1 year periods.

Here we try to extend the external field response out to 11 years.

Constable & Constable (in prep.)

The various bits…



Sun: Source of solar wind (and life on Earth). Magnetic field reverses every ~11 years.

Solar wind: Moderate and varying number of high energy ionized particles. High conductivity, magnetic field ~5 nT.

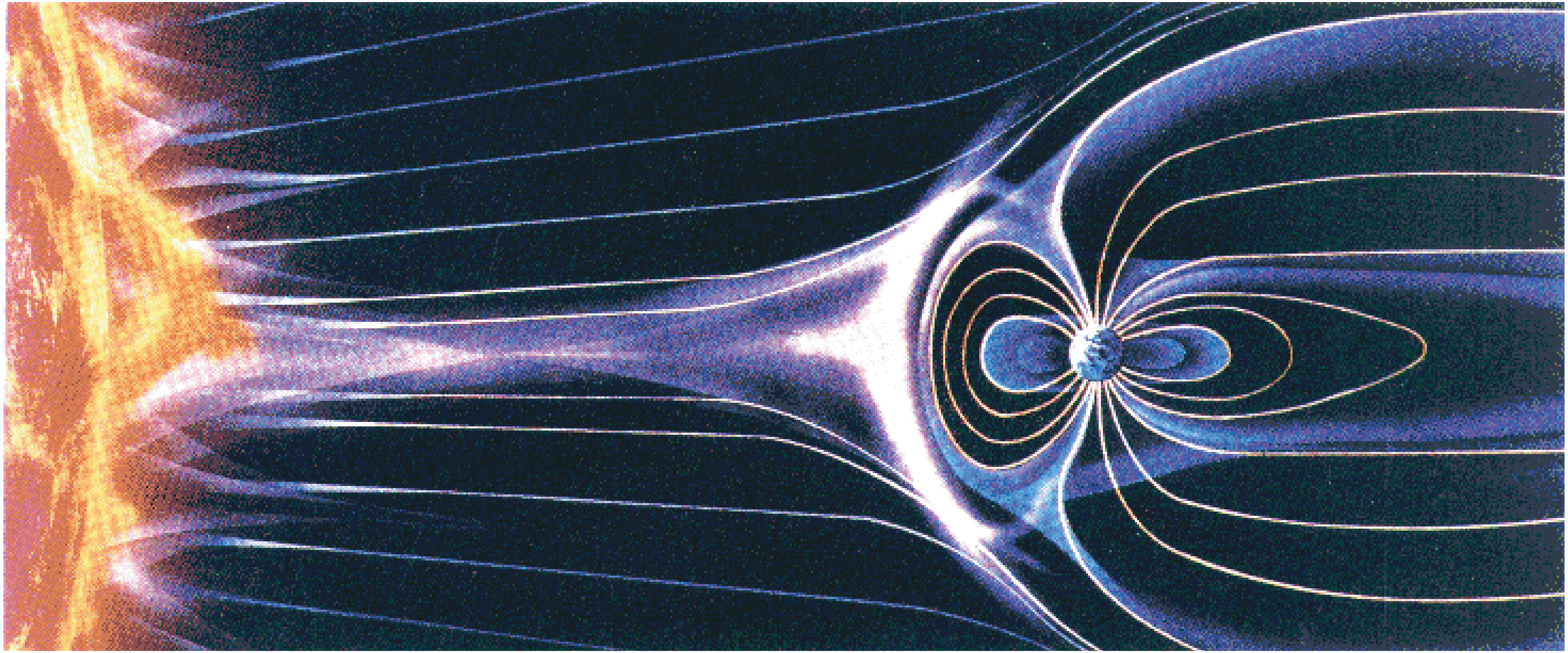
Magnetosphere: Few ionized particles, no particle collisions. Magnetic field 30,000 nT decreasing to ~100 nT. Negligible electric fields. Currents in radiation belts.

Ionosphere: Electrically conductive, many ionized particles, few particle collisions. Smaller electric fields. Currents driven by thermal tides from Sun.

Atmosphere: Electrically resistive, few ionized particles, lots of particle collisions. Large electric fields.

Earth: Electrically conductive, from water, mineral, and core conductivity.

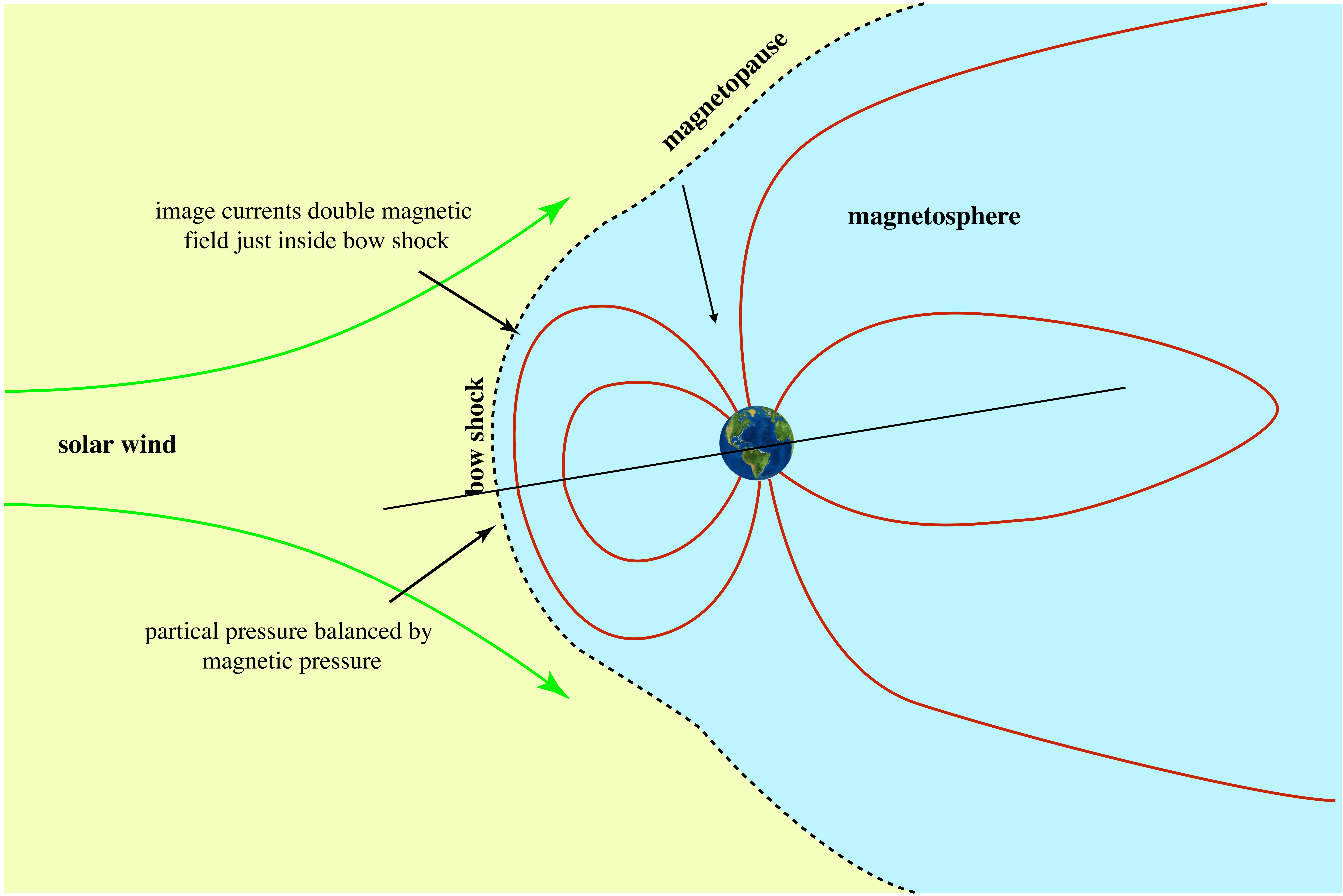
The solar wind pushes and deflects Earth's magnetic field, eventually being largely excluded when magnetic pressure gets high enough. Particles "sneak in" around the poles (causing aurora) and the night side to create Van-Allen radiation belts, or the ring current. Interplanetary magnetic field ~5 nT.



The solar wind consists of a plasma, ionized protons and electrons with a particle density of $N \sim 6 \times 10^6\ m^{-3}$ moving at about 4.5×10^5 m/s when it reaches Earth.

It is supersonic, so the collision point creates a bow shock.

It is highly conductive, so a current flows to create an image field that prevents a normal component of B at the magnetopause.



Balancing the pressure of the solar wind, which is mainly from proton momentum, and magnetic field pressure allows us to make an estimate of the bow shock location.

The pressure of the solar wind is given by the kinetic energy density of the protons

$$P_{KE} = \frac{1}{2}\rho v^2 = \frac{1}{2} N m_p v^2 \approx 1 \times 10^{-9} \text{ Pa}$$

The magnetic field energy density is $P_B = \frac{B^2}{2\mu_o}$ so $B^2 = \mu_o N m_p v^2$ or about 50 nT.

Taking into account the image field, the Earth field will be half this, or 25 nT. The dipole field falls off as R^{-3}, so

$$B(R) = B(a)\left(\frac{a}{R}\right)^3$$

where *B(a)* is the field at the surface, or about 30,000 nT at the equator. So we compute the bow shock at

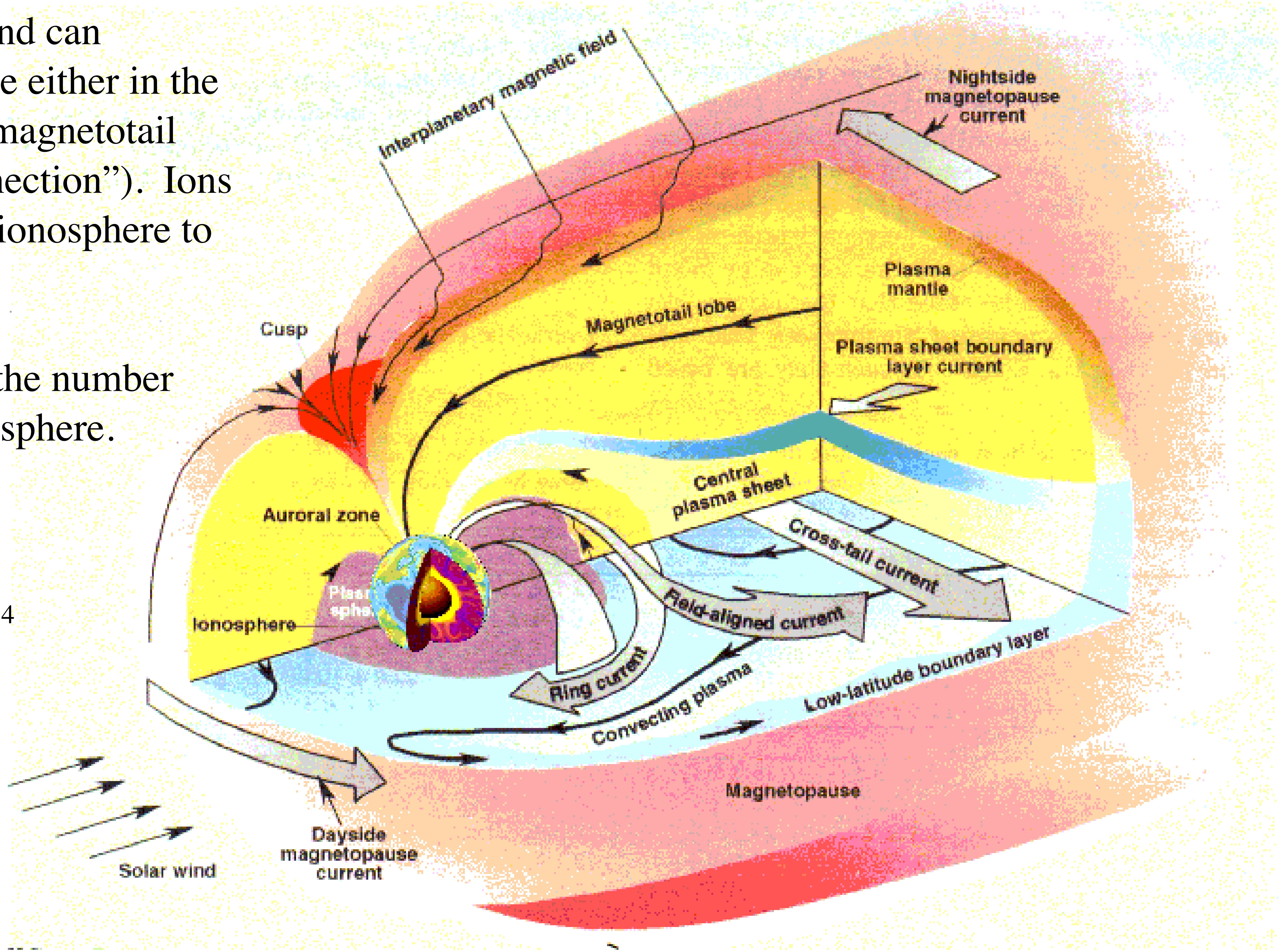
$$(a/R)^3 = 30,000/25 = 1200$$ or about 11 Earth radii.

Particles from the solar wind can penetrate the magnetopause either in the auroral zones or from the magnetotail (through "magnetic reconnection"). Ions also "evaporate" from the ionosphere to form the plasmosphere.

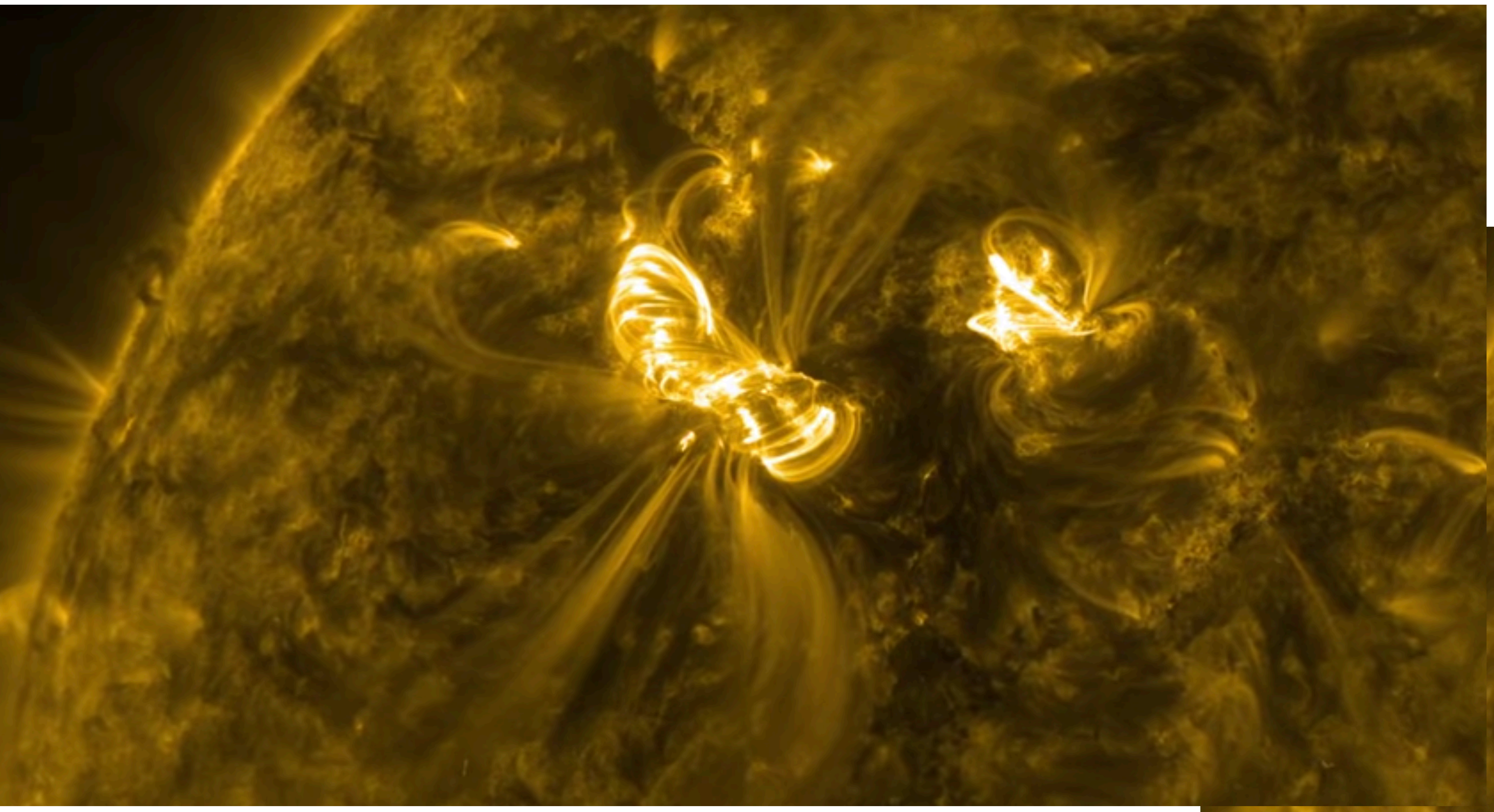
Magnetic storms increase the number of particles in the magnetosphere.

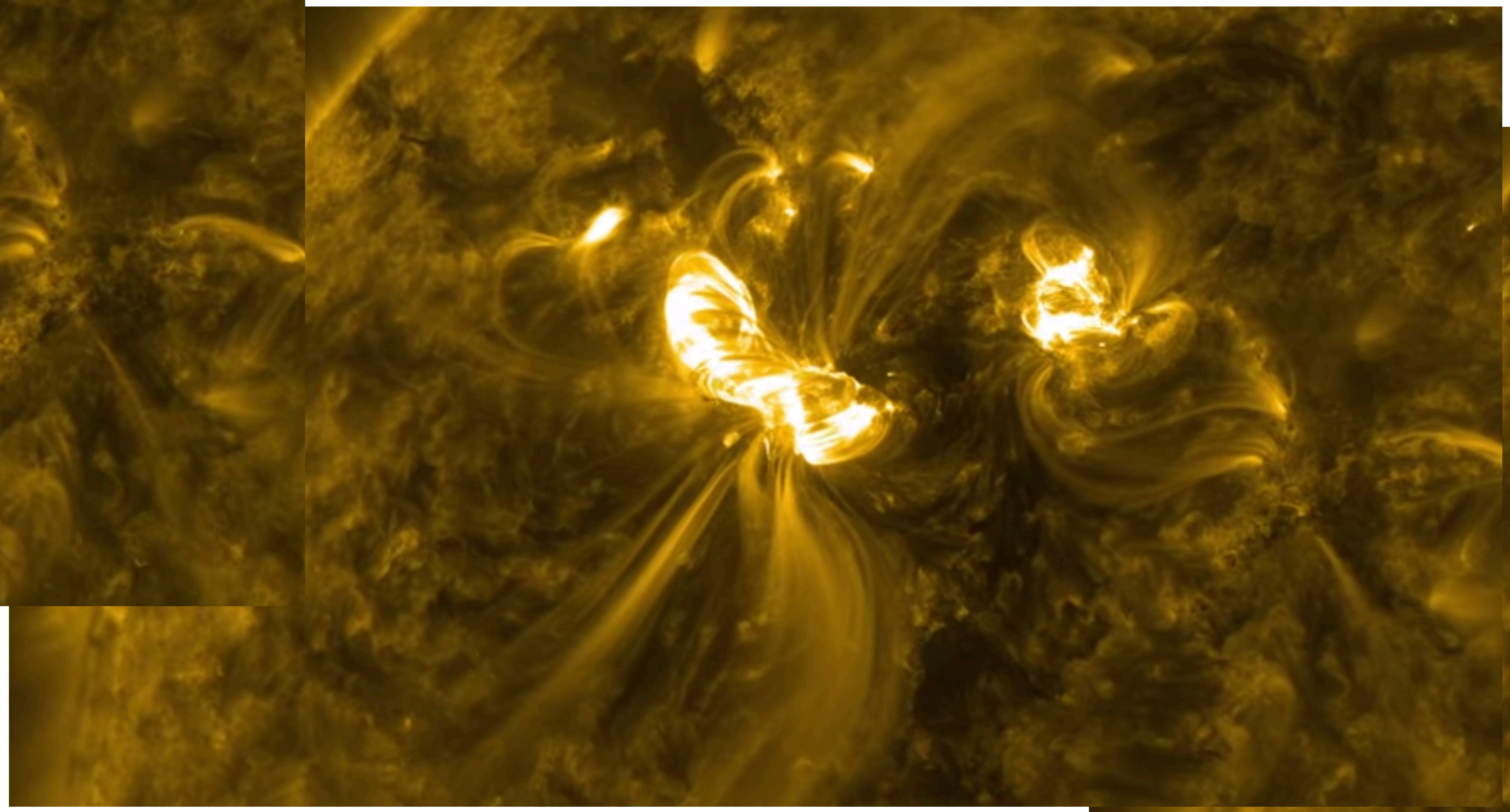
Once in, particles are essentially collisionless, with mean free paths of 10^4 to 10^{12} km.

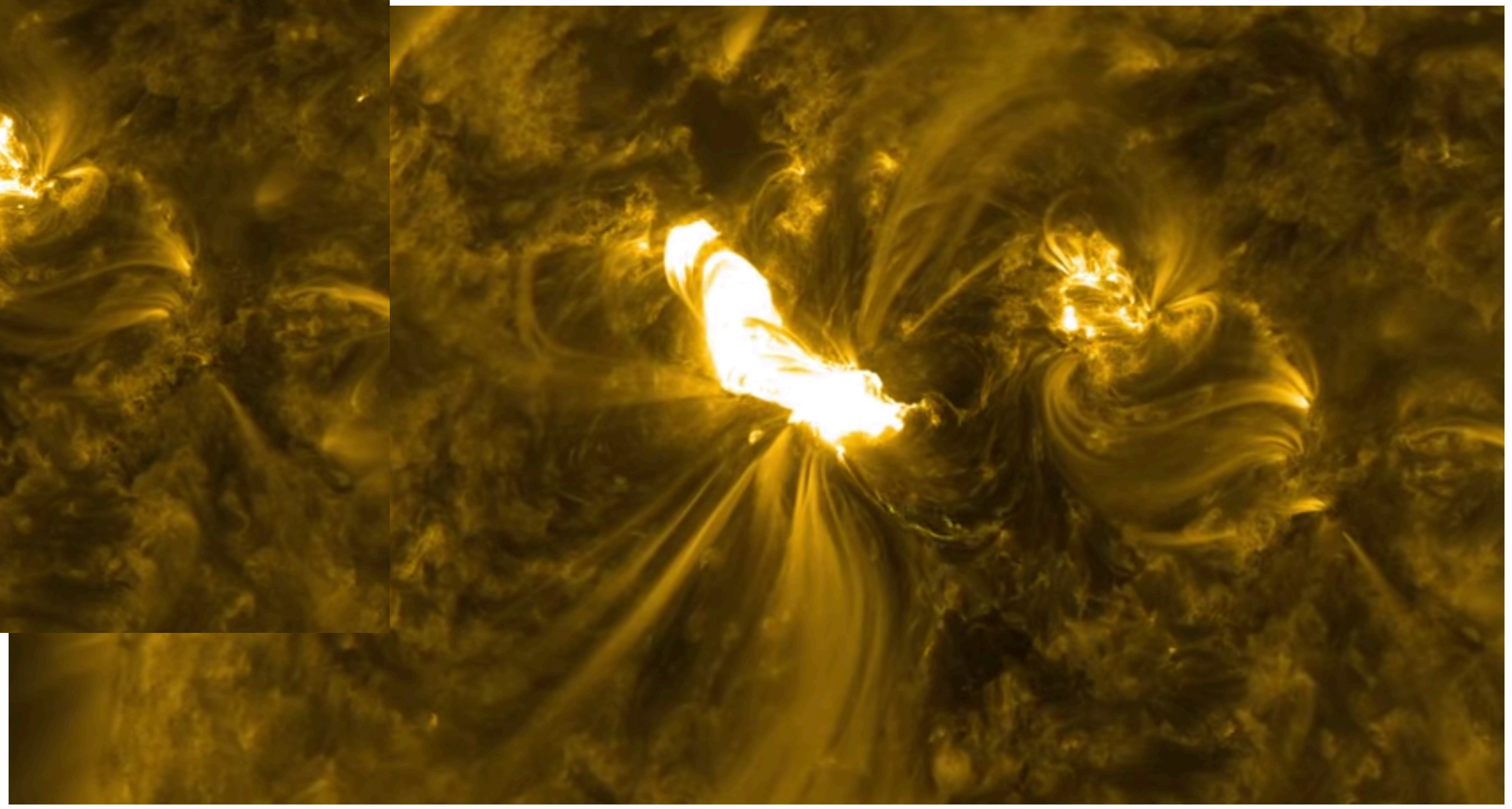
There are many current systems, but the most important is the ring current.



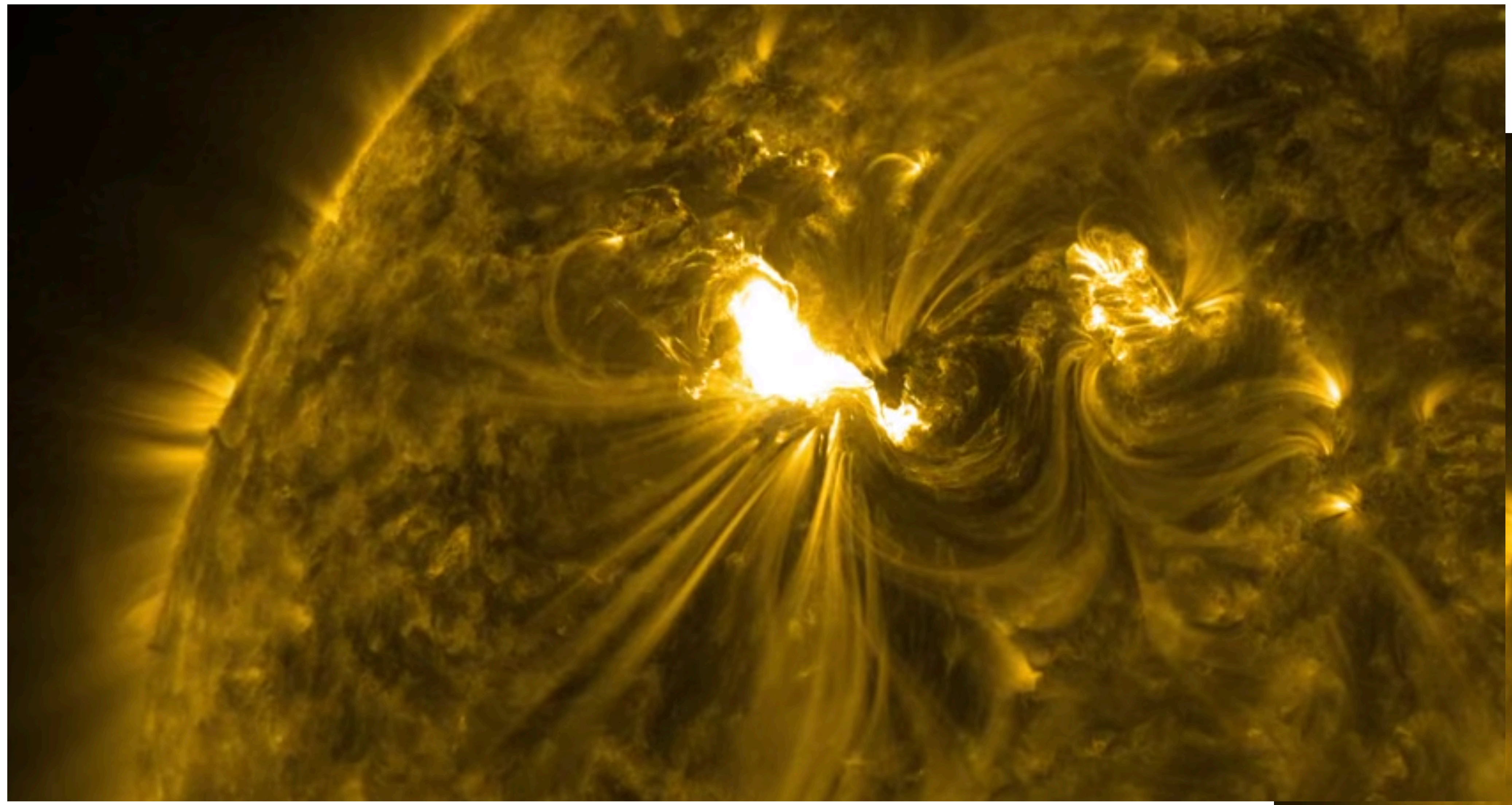
Magnetic storms are associated with coronal mass ejections.

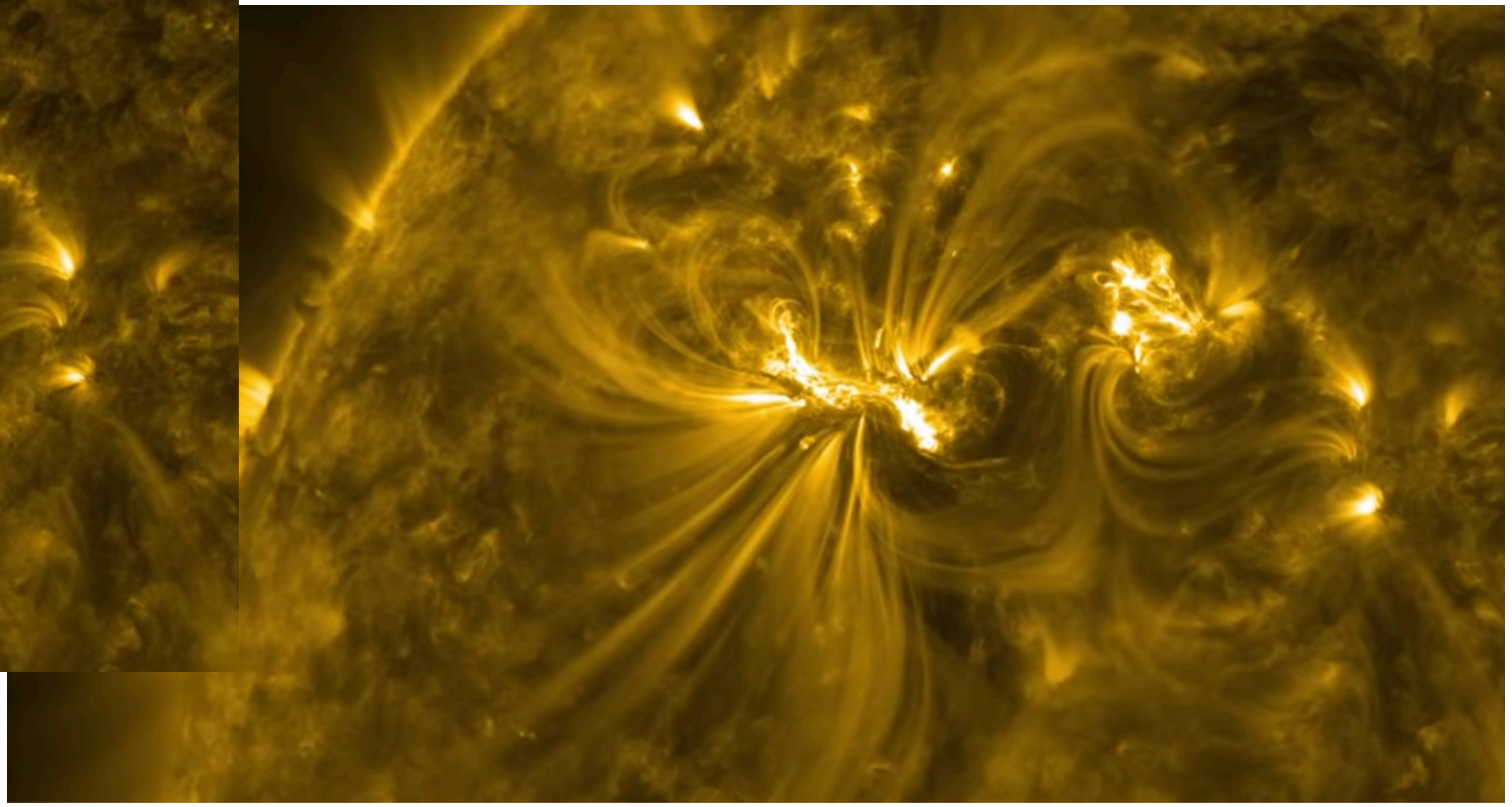




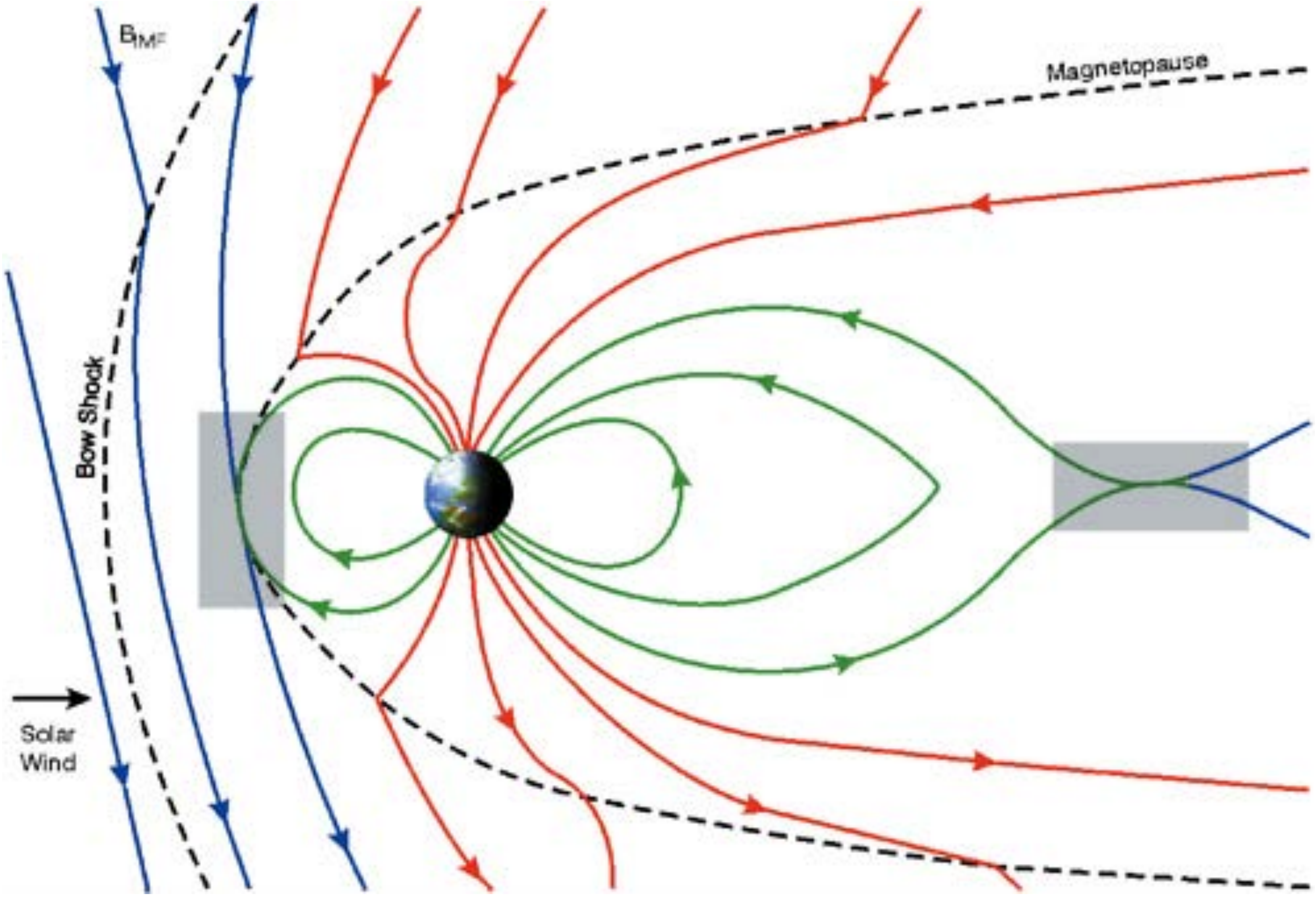


These are also magnetic reconnection phenomena.





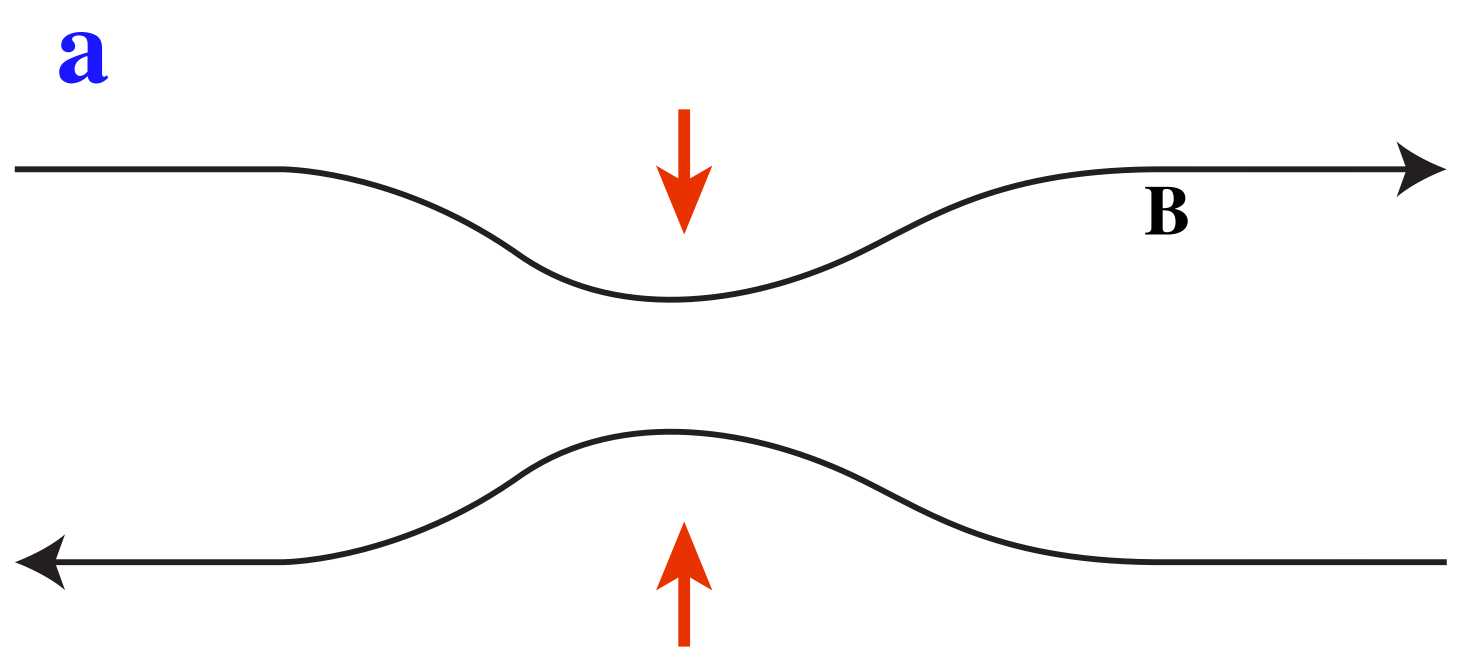
NASA images of March 7, 2012 flare.



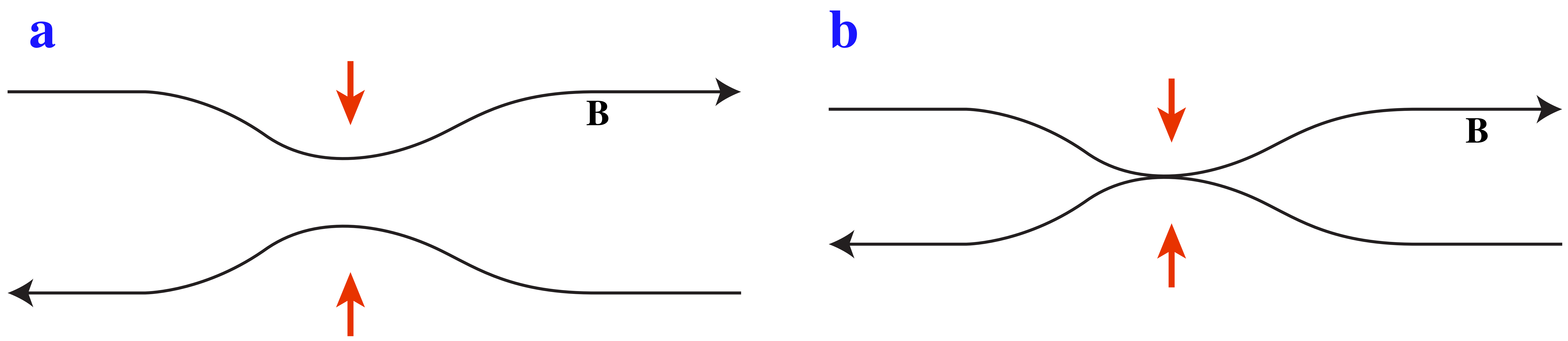
https://www.cfa.harvard.edu/~namurphy/Lectures/Ay253_2016_11_MagneticReconnection.pdf

https://www.youtube.com/watch?v=mgUZwoR0gcE

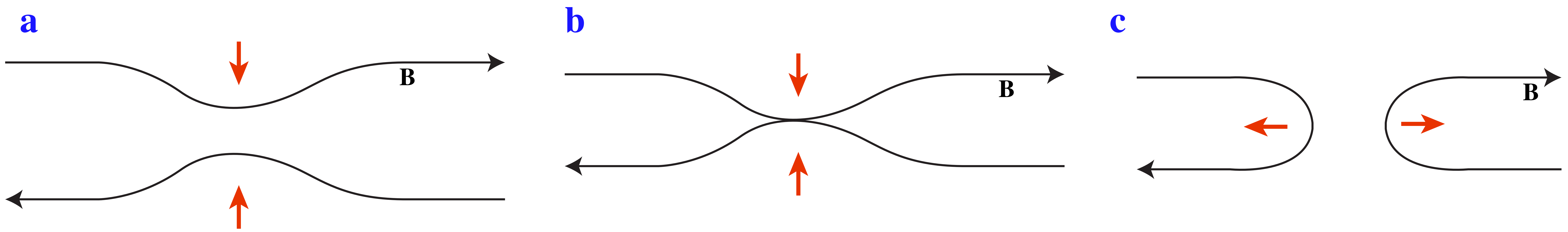
Magnetic reconnection in a plasma: Magnetic field energy converted to kinetic energy.



Magnetic reconnection in a plasma: Magnetic field energy converted to kinetic energy.

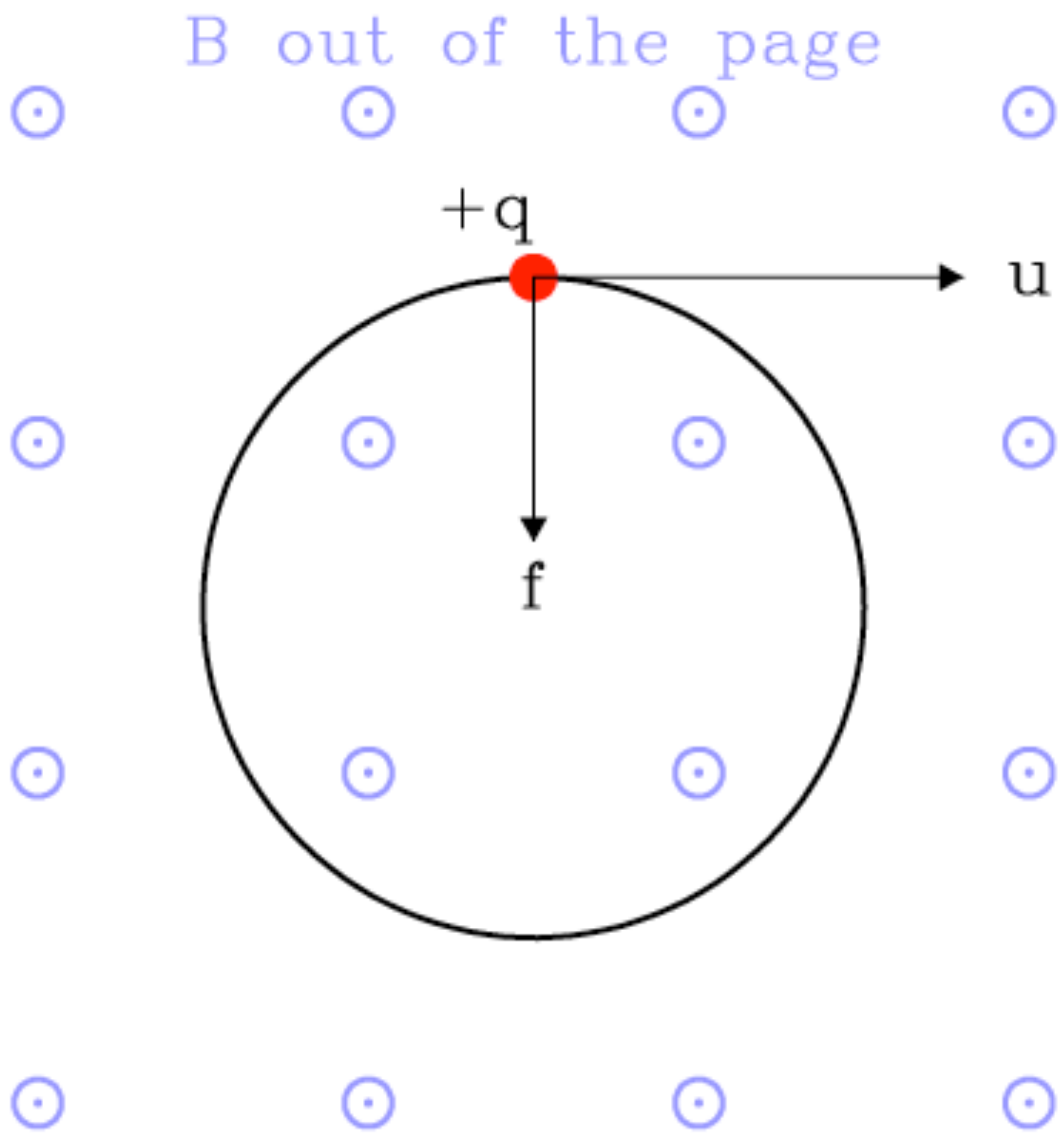


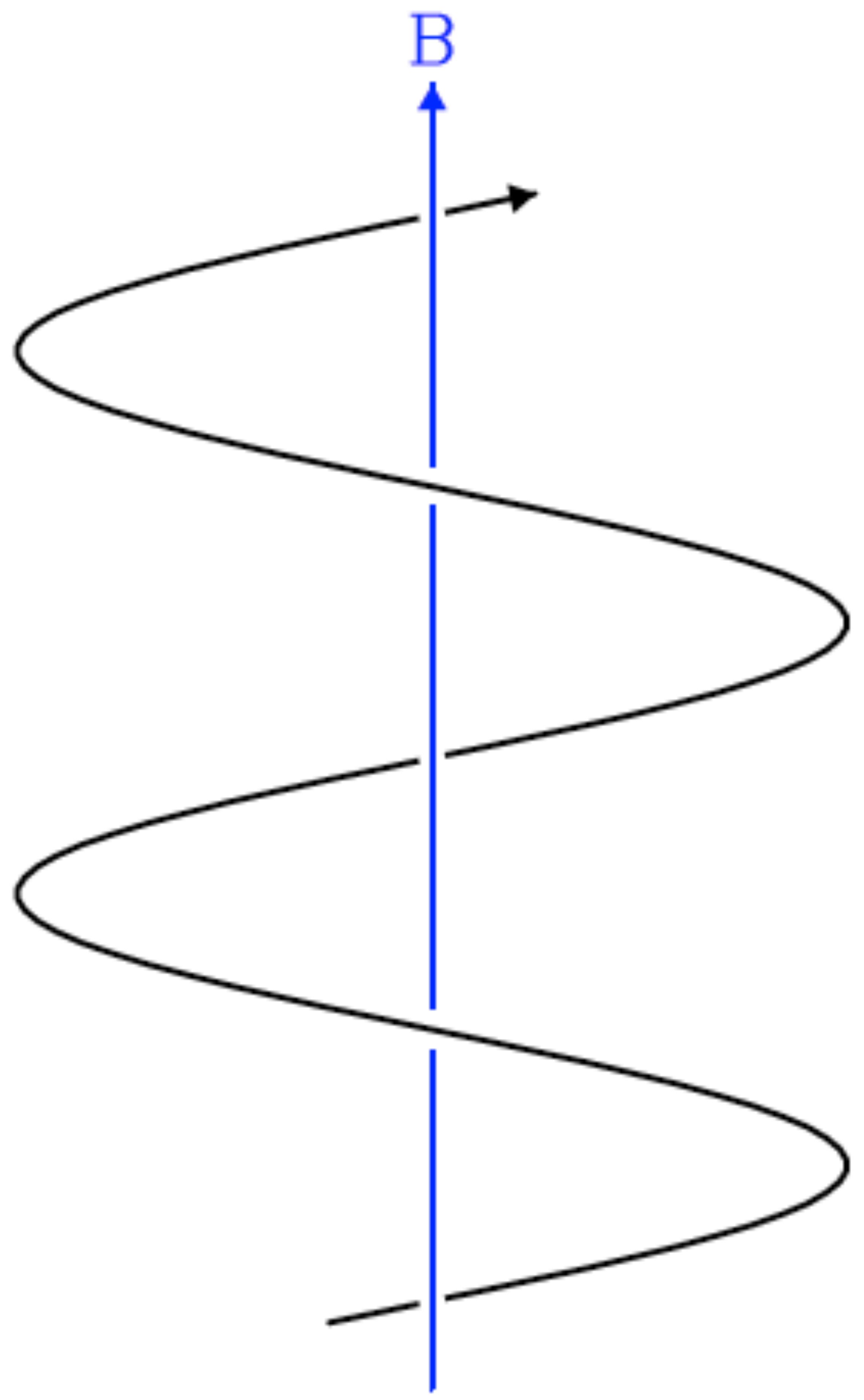
Magnetic reconnection in a plasma: Magnetic field energy converted to kinetic energy.



Any particle finding itself in the magnetosphere will be subject to our friend the Lorentz force. A particle with velocity u that cuts across the lines of magnetic field will be turned into a circular path. Any component of velocity parallel to the field is left unaltered, so the particle will spiral along the field if it has such velocity.

$$\mathbf{F} = q(\mathbf{E} + \mathbf{u} \times \mathbf{B})$$





Radiation belts and ring current: For charge q

$$\mathbf{f} = q(\mathbf{u} \times \mathbf{B})$$

so from $f = ma$ acceleration is

$$\frac{d\mathbf{u}}{dt} = \frac{q}{m}\mathbf{u} \times \mathbf{B}$$

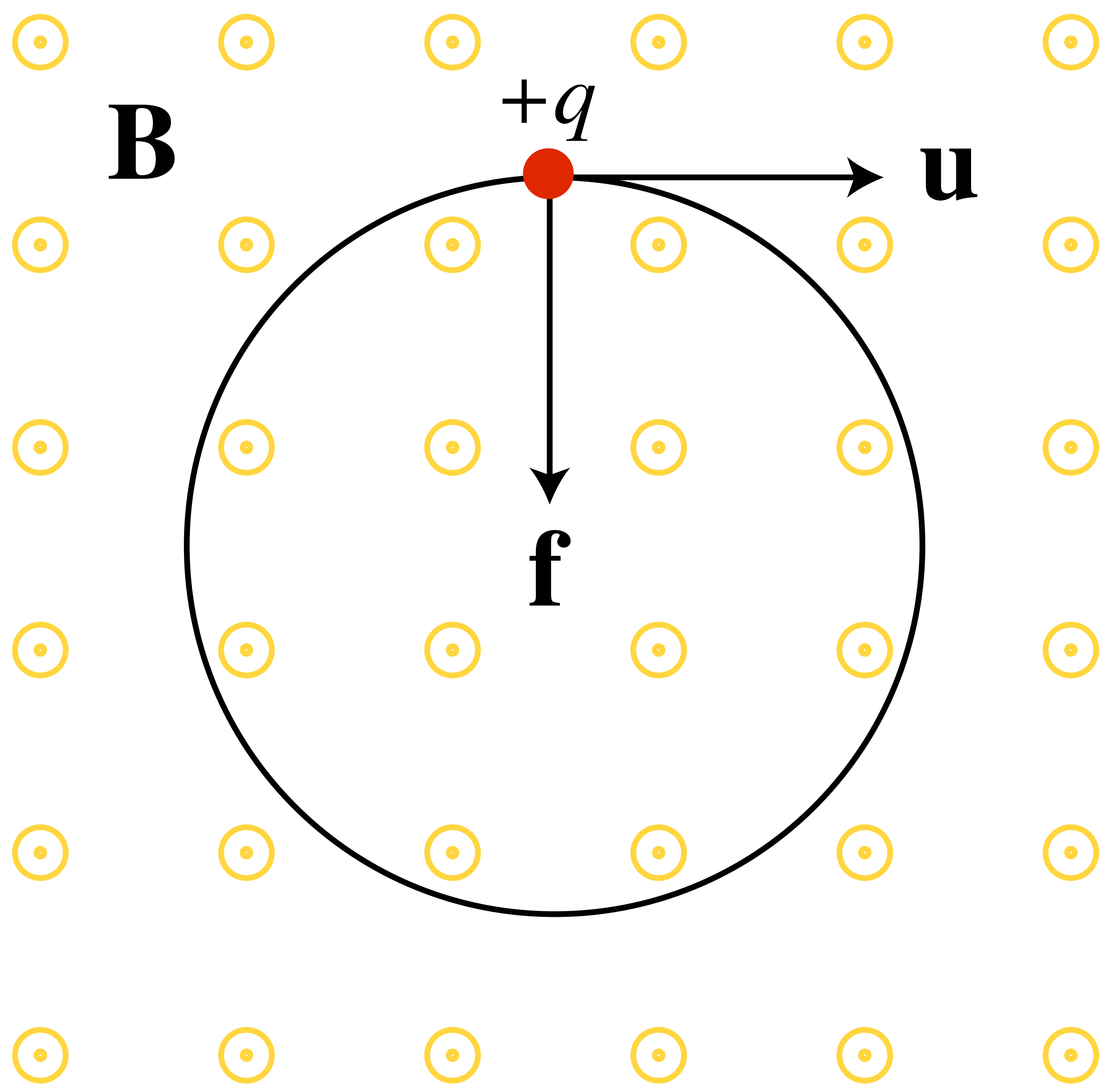
Rewriting in terms of angular velocity and acceleration

$$r\omega = |\mathbf{u}| \qquad r\omega^2 = \left|\frac{d\mathbf{u}}{dt}\right|$$

and so

$$\omega = \frac{q}{m}|\mathbf{B}| \qquad r = \frac{m}{q}\frac{|\mathbf{u}|}{|\mathbf{B}|}$$

(ω is the cyclotron frequency, or gyrofrequency)

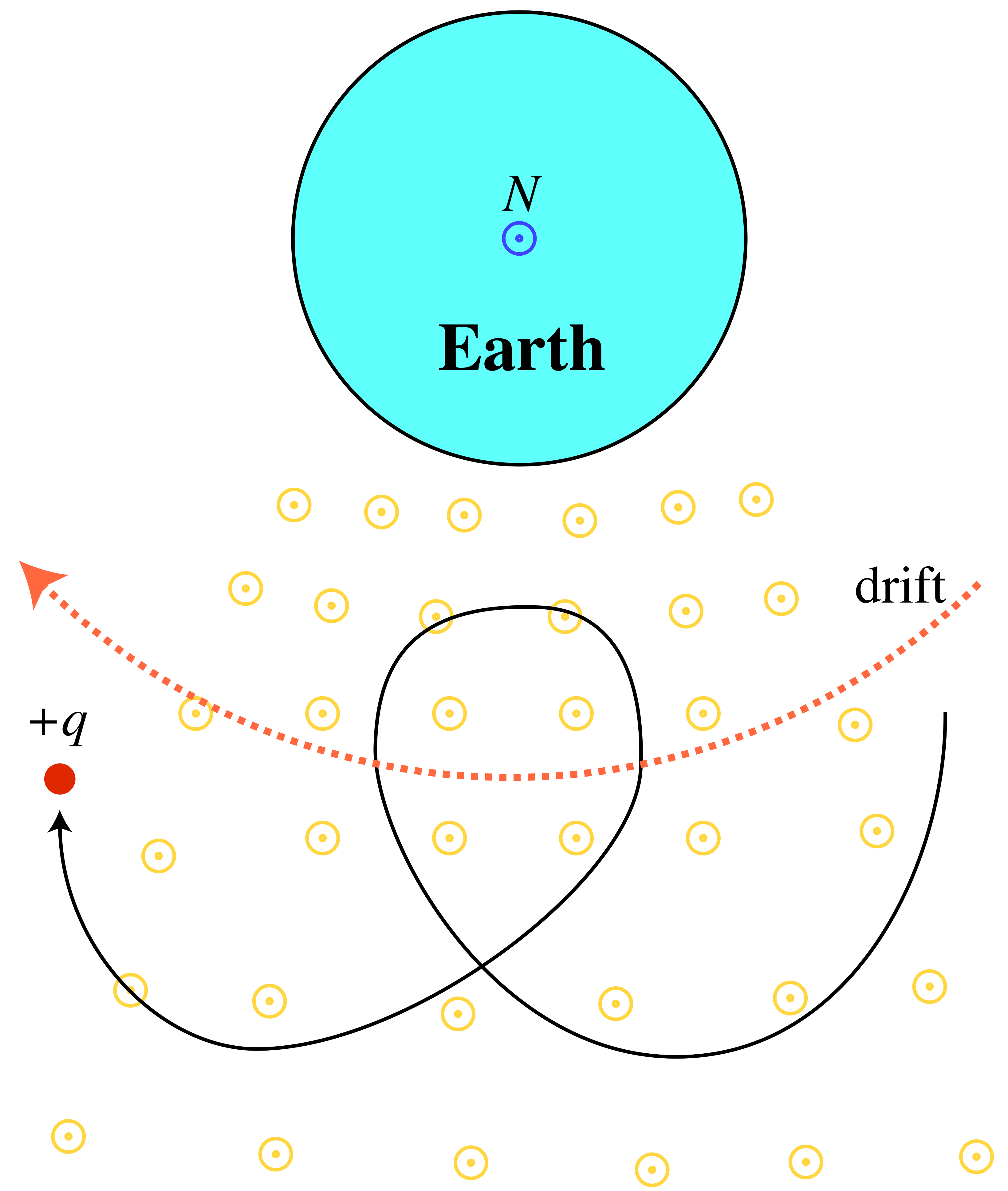


Another way of getting r is to balance centrifugal force with Lorentz force:

$$\frac{mu^2}{r} = quB$$

$$r = \frac{mu}{qB}$$

Because Earth's magnetic field falls off with distance, gyration radius is smaller on the close side of the particle path and there is a net westward movement of charge. This is the geomagnetic ring current. It opposes Earth's main field.

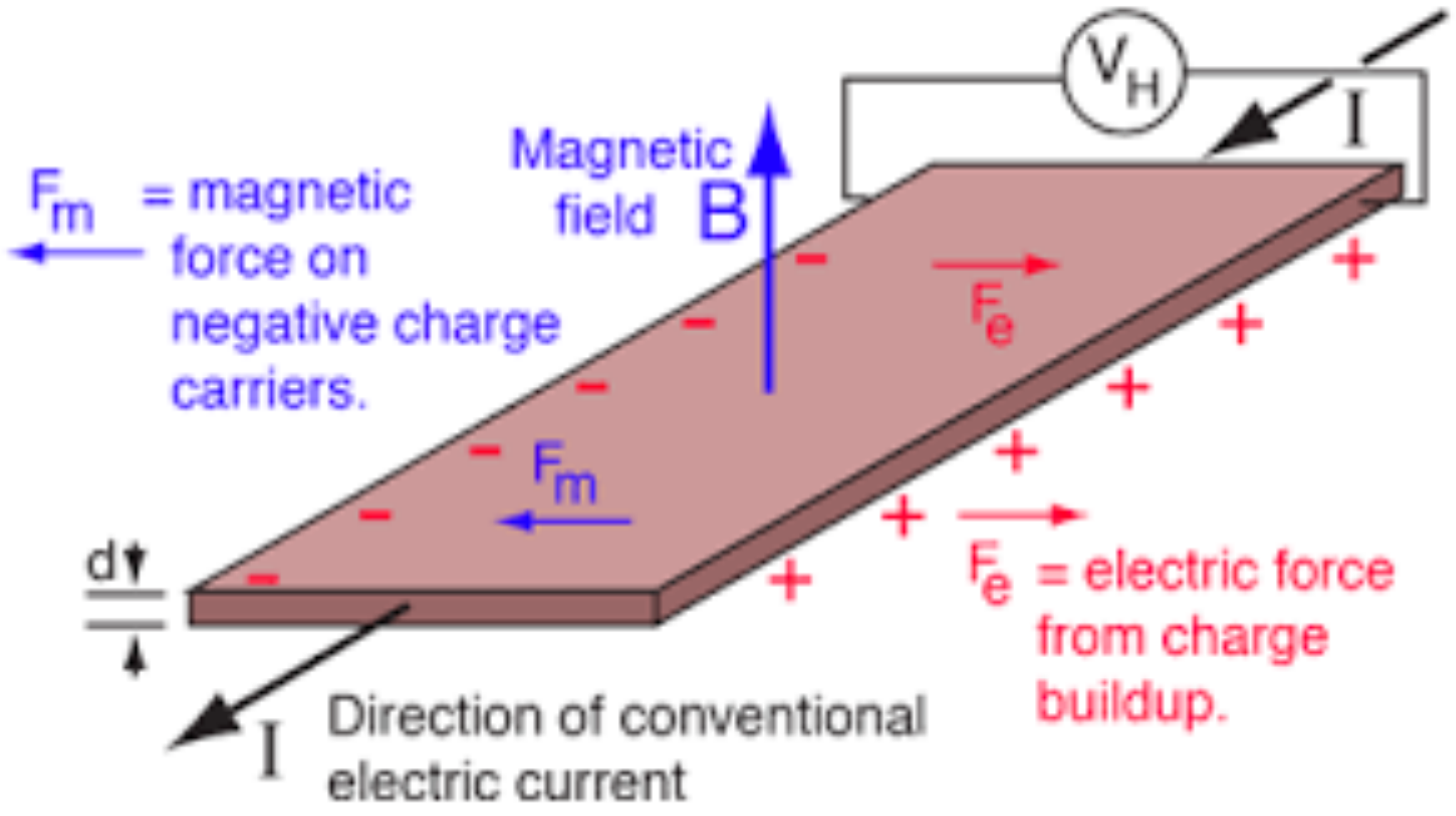


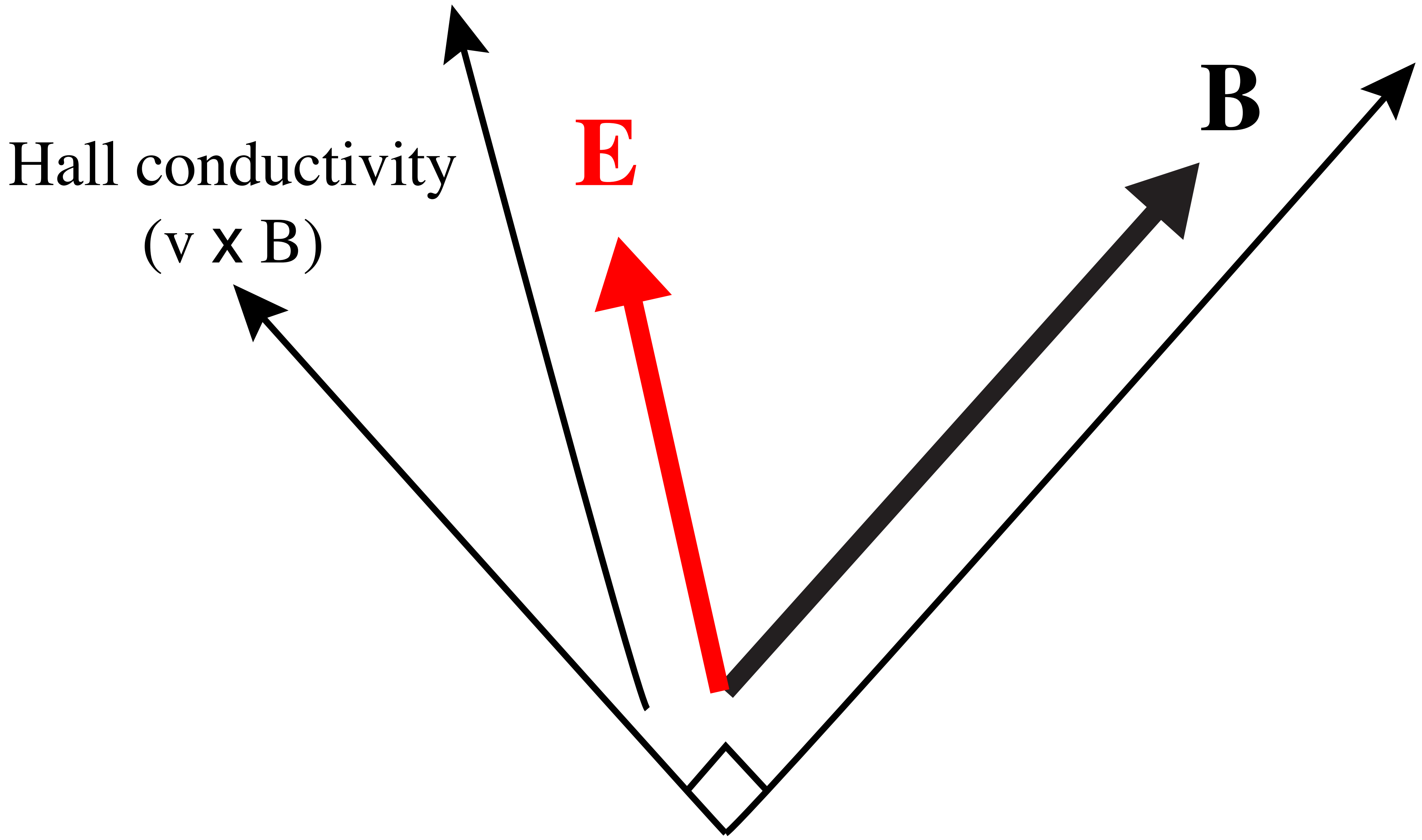
The ring current is also sustained by a Hall current:

$$q(\mathbf{E} + \mathbf{u} \times \mathbf{B}) = \mathbf{f} = ma$$

When **E** is perpendicular to **B** we get an acceleration perpendicular to both fields, which for a radial electric field is westward and given by

$$v = -\frac{E}{B}$$





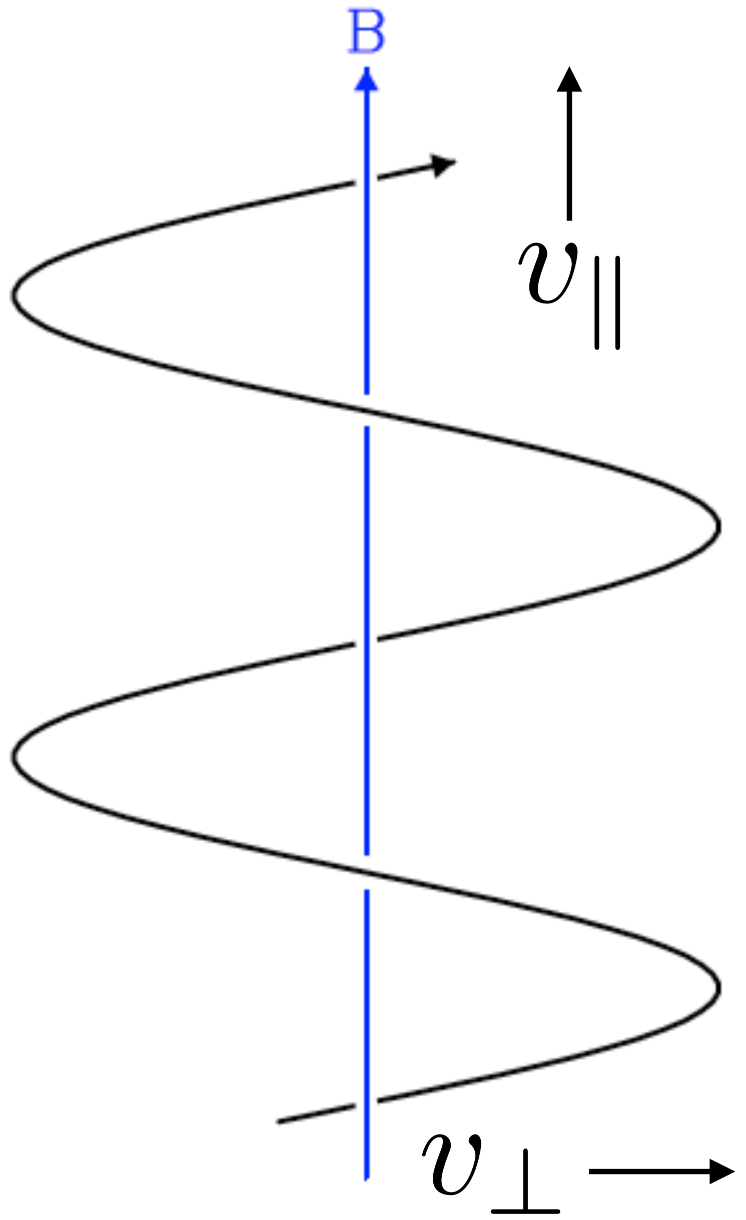
Magnetic mirroring:

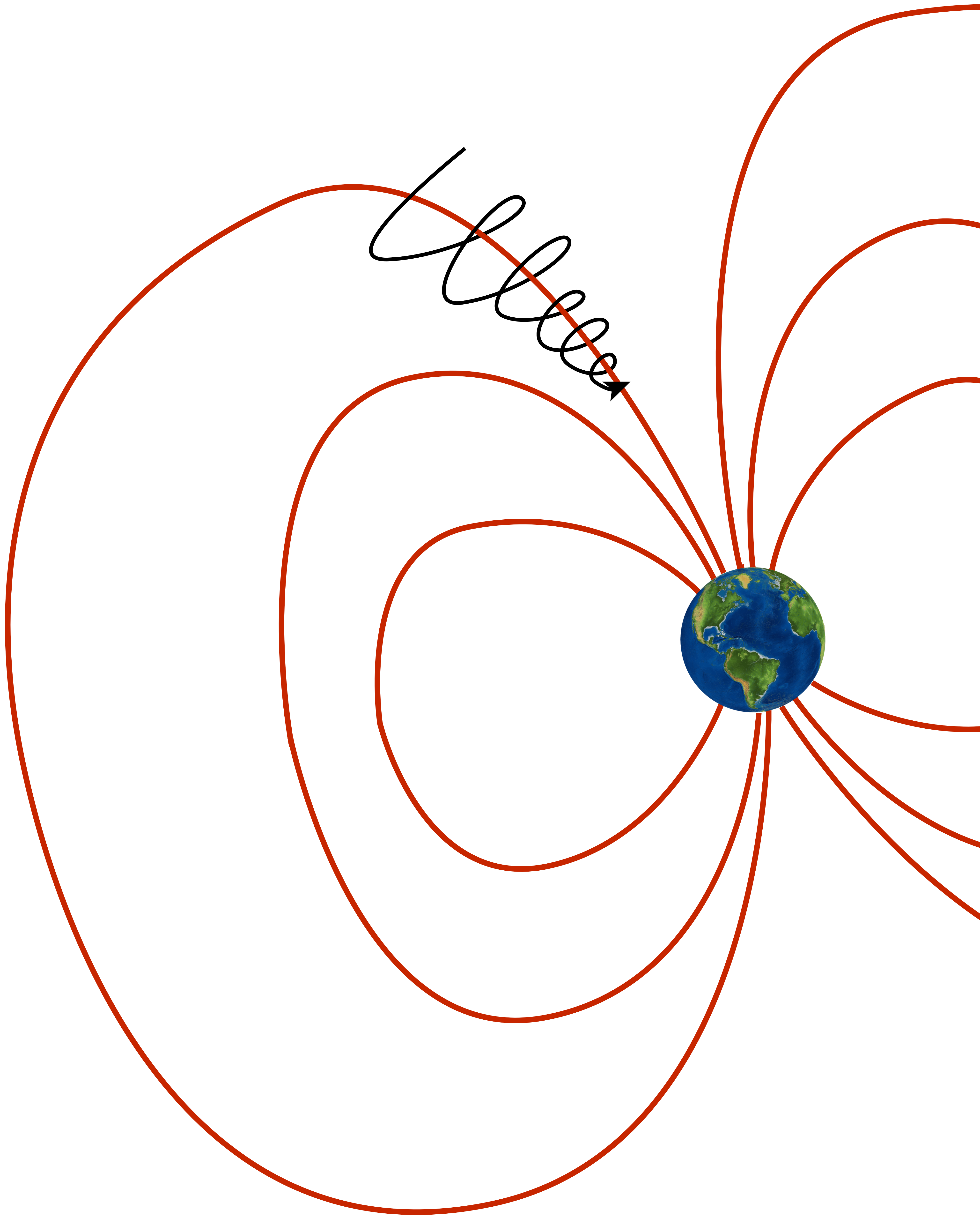
The magnetic moment

$$\mu = \frac{mv_\perp^2}{2B}$$

and total energy

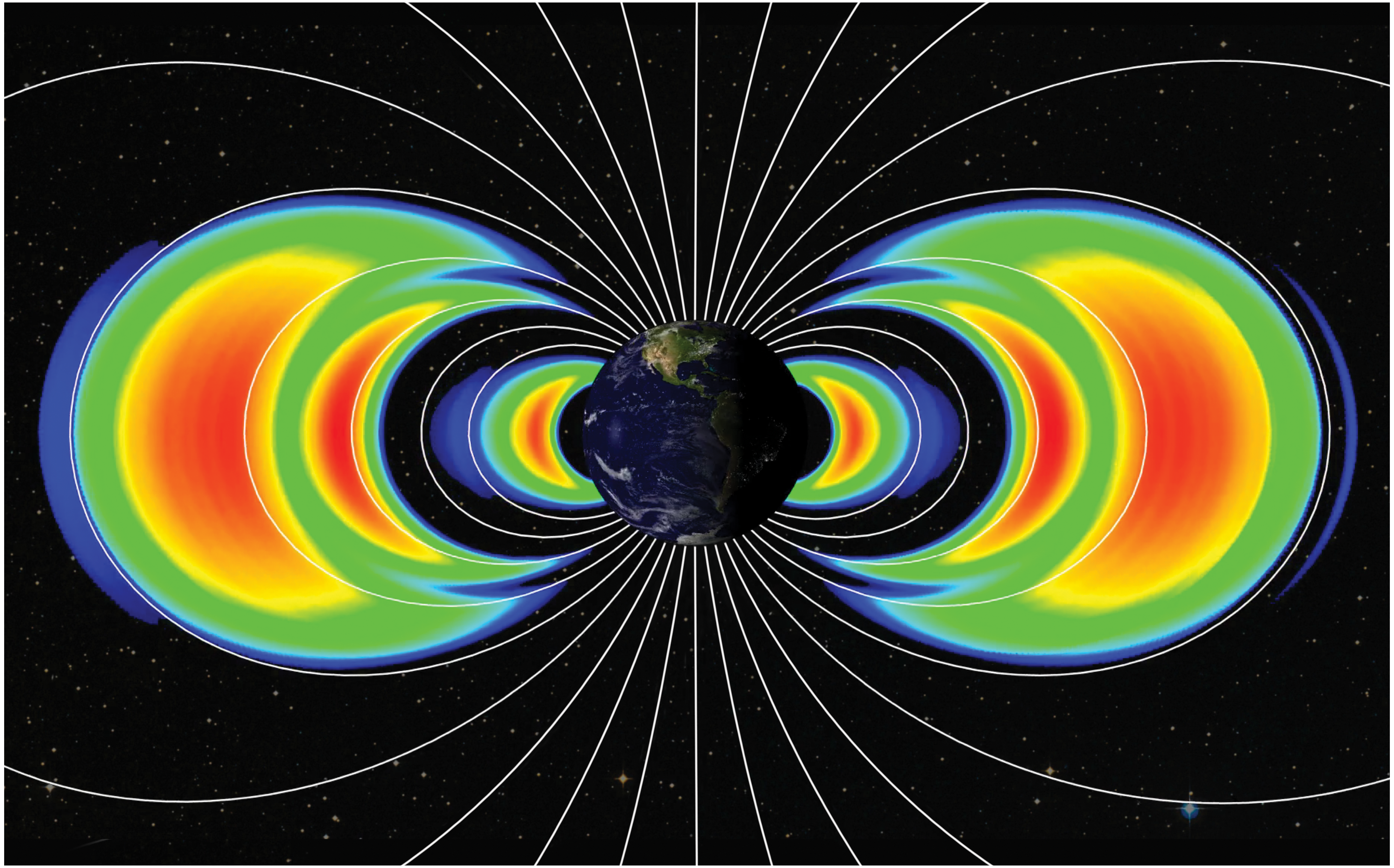
$$\varepsilon = \frac{1}{2}mv_\parallel^2 + \frac{1}{2}mv_\perp^2$$





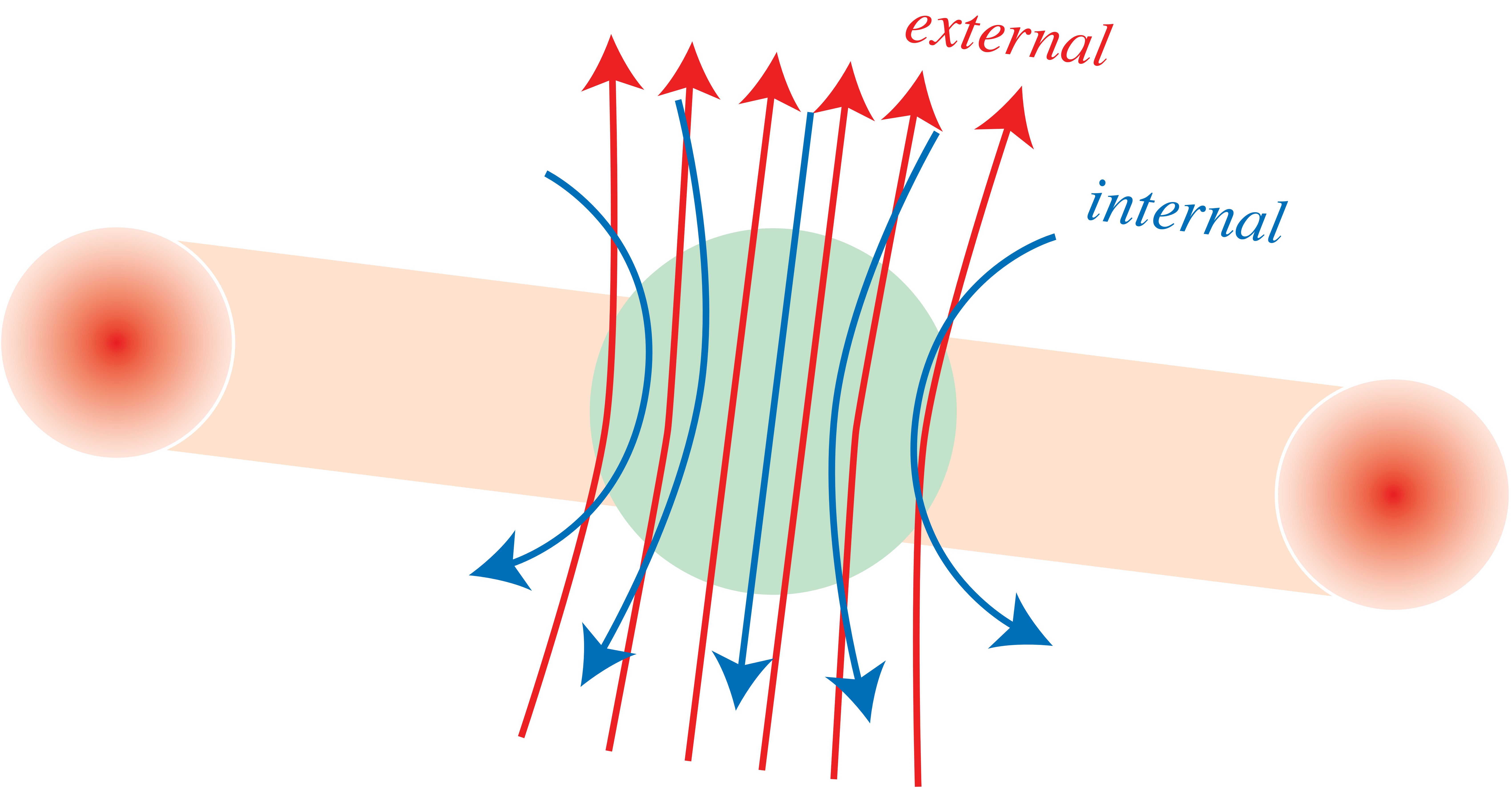
are conserved. As B increases as a particle travels along a field line towards a pole, $v_\perp$ must increase, which means that $v_\parallel^2$ must decrease. At some point $v_\parallel^2$ must go negative, which is impossible since velocity cannot become imaginary, and so the particle is excluded and $v_\parallel$ reverses.

There are two radiation belts, an inner belt at 0.2 to 2 *a* that may be fed from the atmosphere and ionosphere, and an outer belt at 3 to 9 a that is fed by the solar wind and magnetic storms. This picture from the Van Allen probe mission shows the transient splitting of the outer belt into two belts.

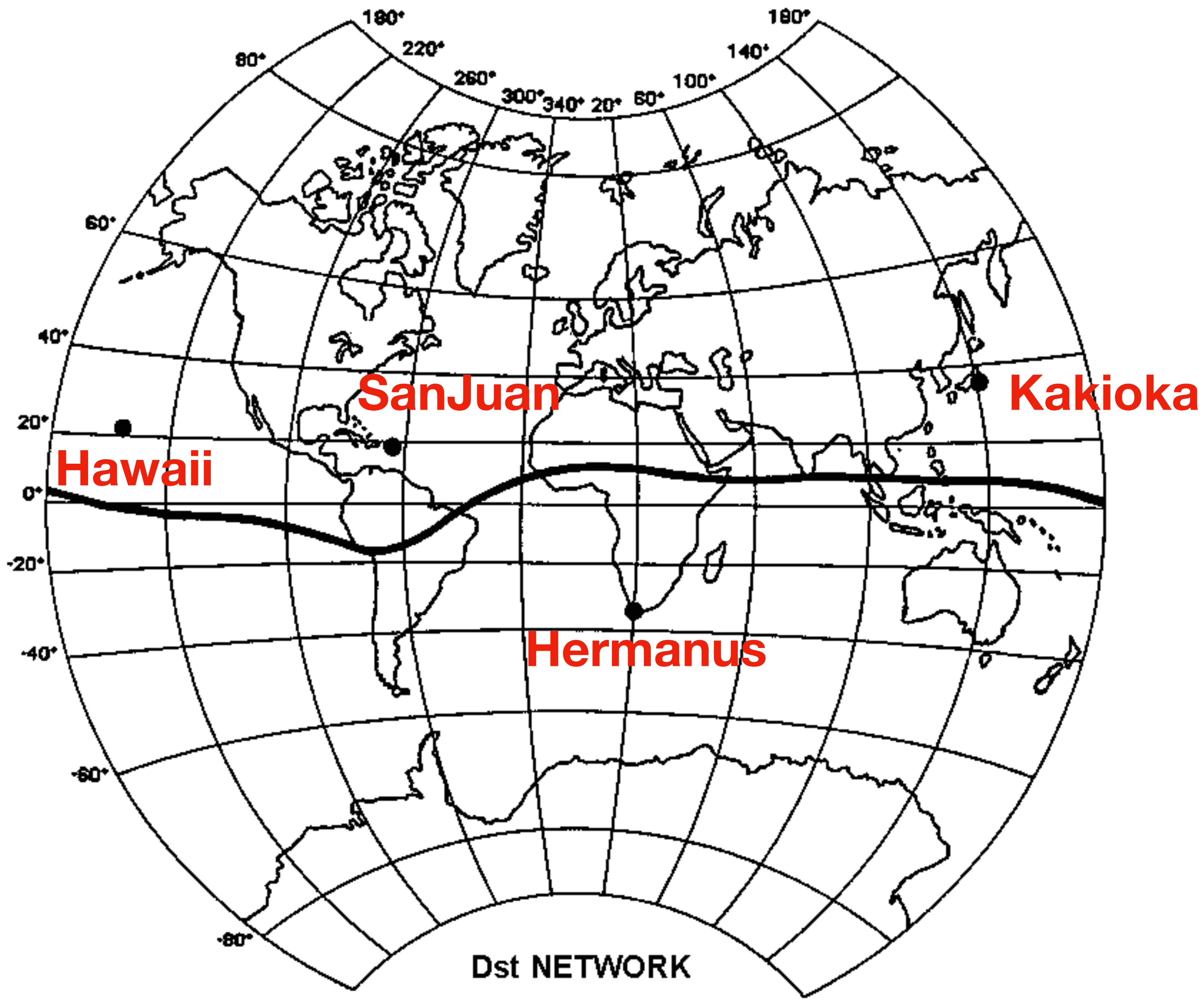


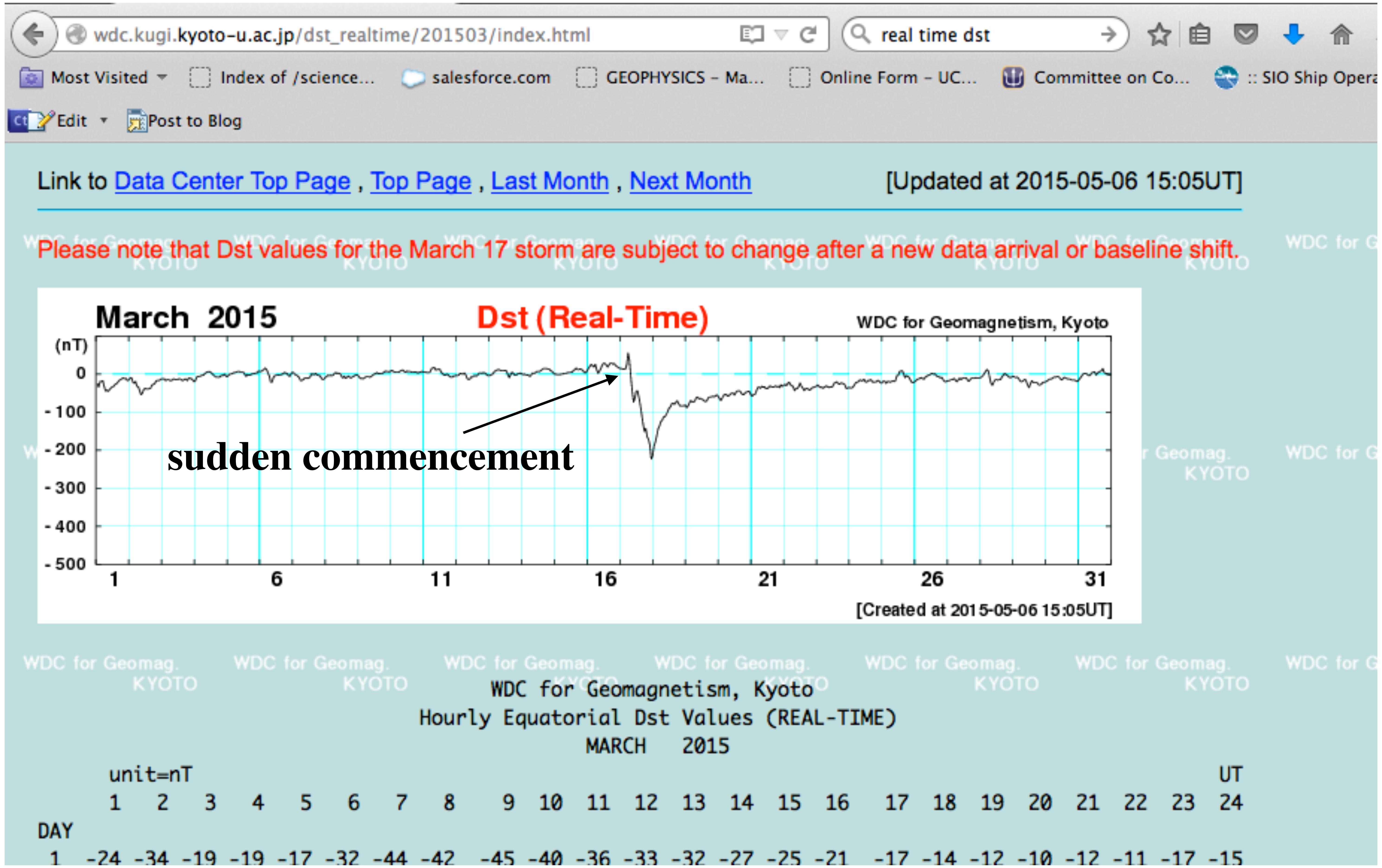
https://svs.gsfc.nasa.gov/hyperwall/index/download/a030000/a030400/a030470/van_allen_probes_discov_new_rad_belt_cal.png

The ring current is tied to the geomagnetic coordinate system (i.e. it is symmetric about the geomagnetic equator, not the geographic equator). The morphology is mainly that of a P^1_0 spherical harmonic geometry, but with some day-side/night-side asymmetry. It acts to decrease Earth's field at the surface.

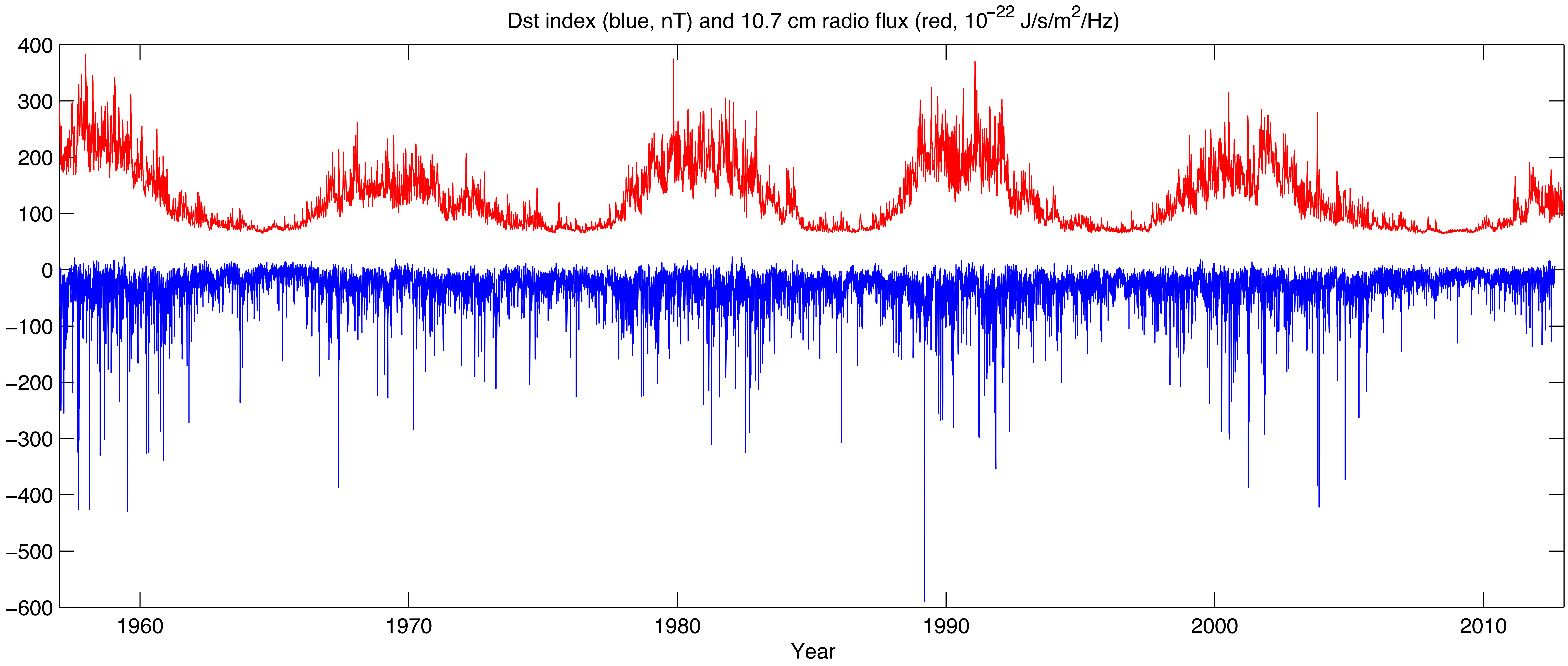


Particles from the sun and magnetic storms inject particles into the ring current. The size of the ring current generated by solar activity is measured using the Dst index ("disturbed storm time"). Because the effect of the ring current is to *reduce* Earth's main field, storms go negative, but at the beginning of a storm the magnetopause gets briefly compressed and the field increases.



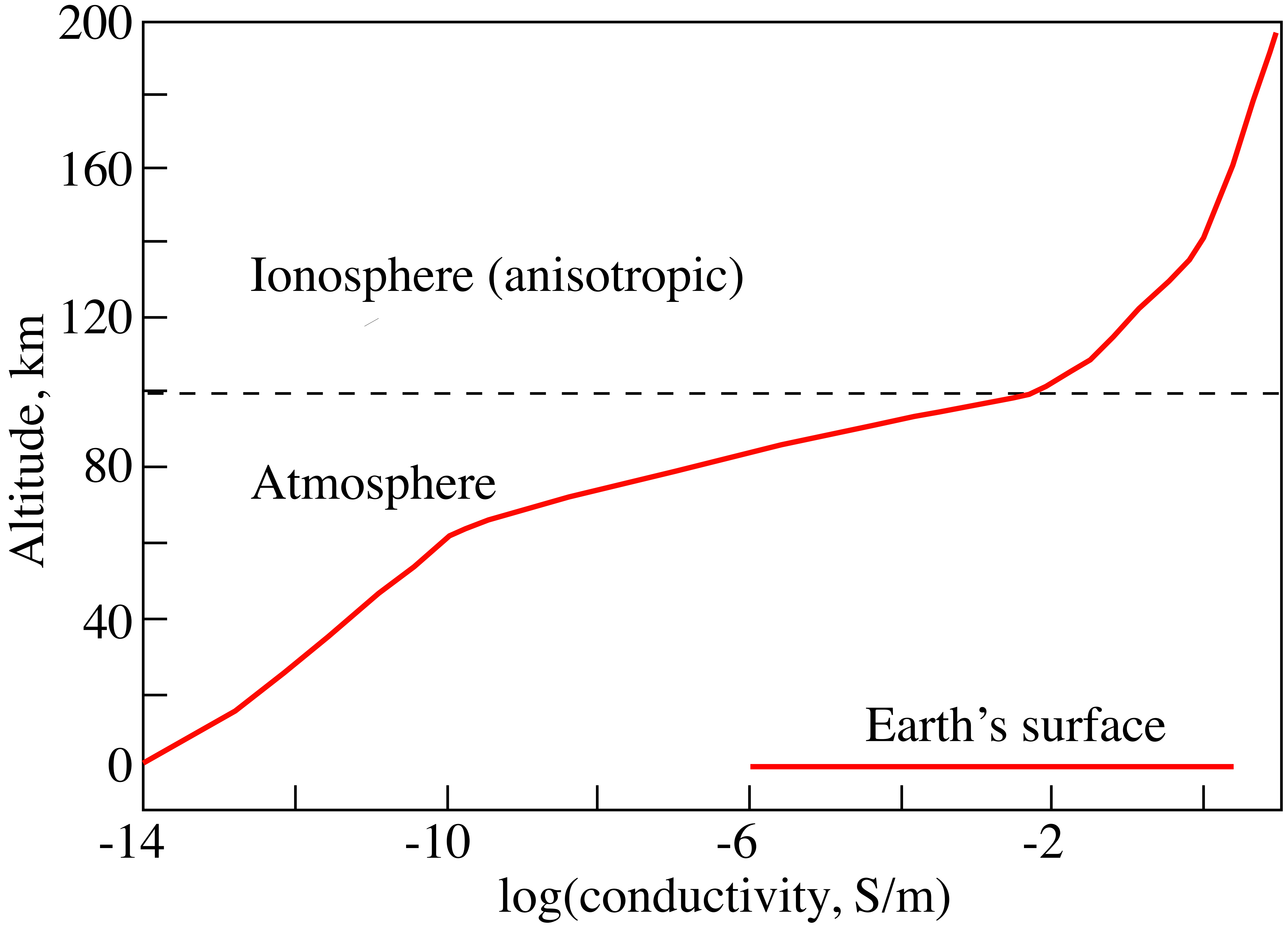


Magnetic storms are tied to the 11-year solar cycle, but not too strongly.

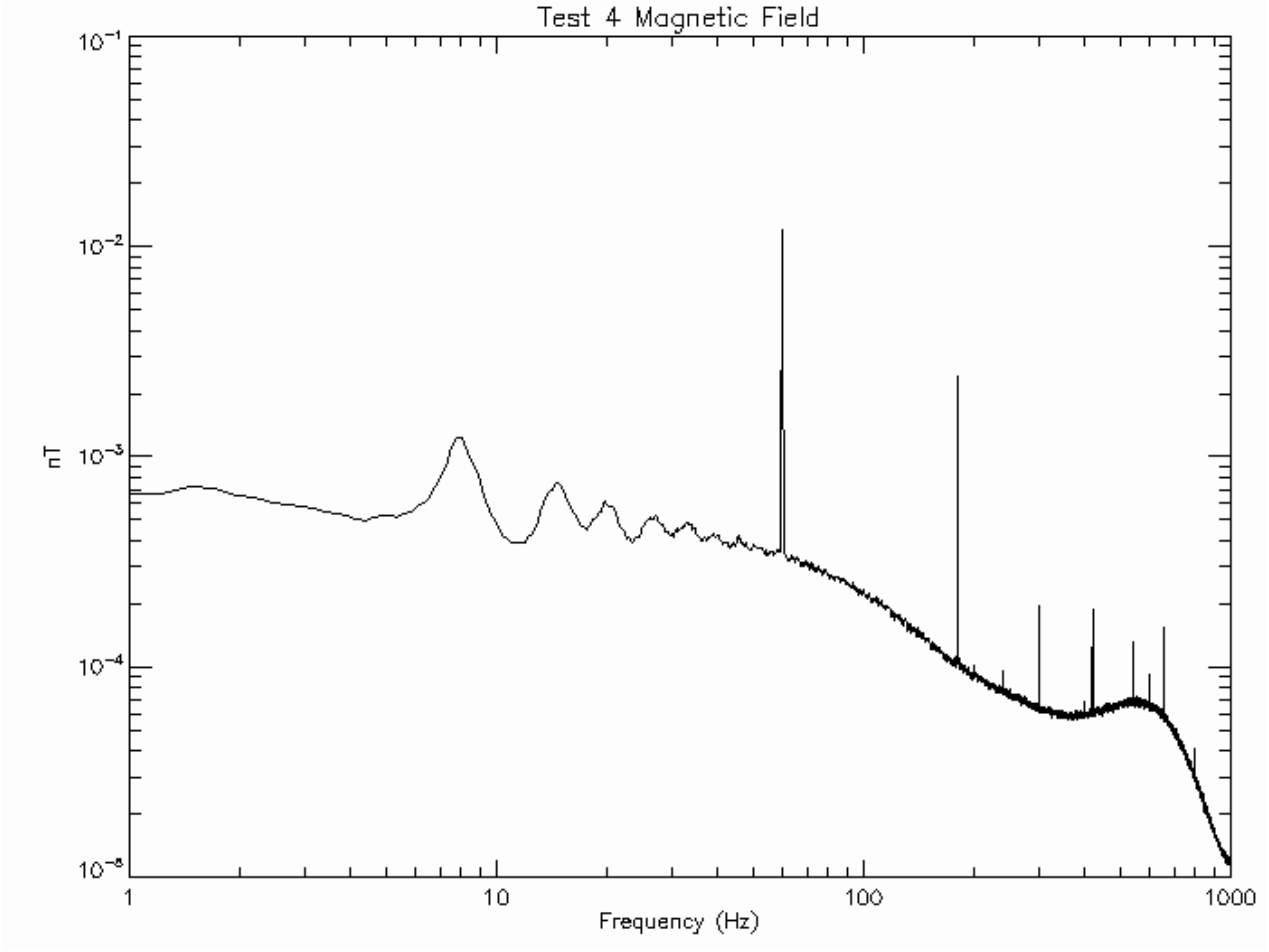


Ionization of O_2 and N_2 from cosmic rays creates charges in the atmosphere. Electrons tend to attach to particles, positive ions remain free.

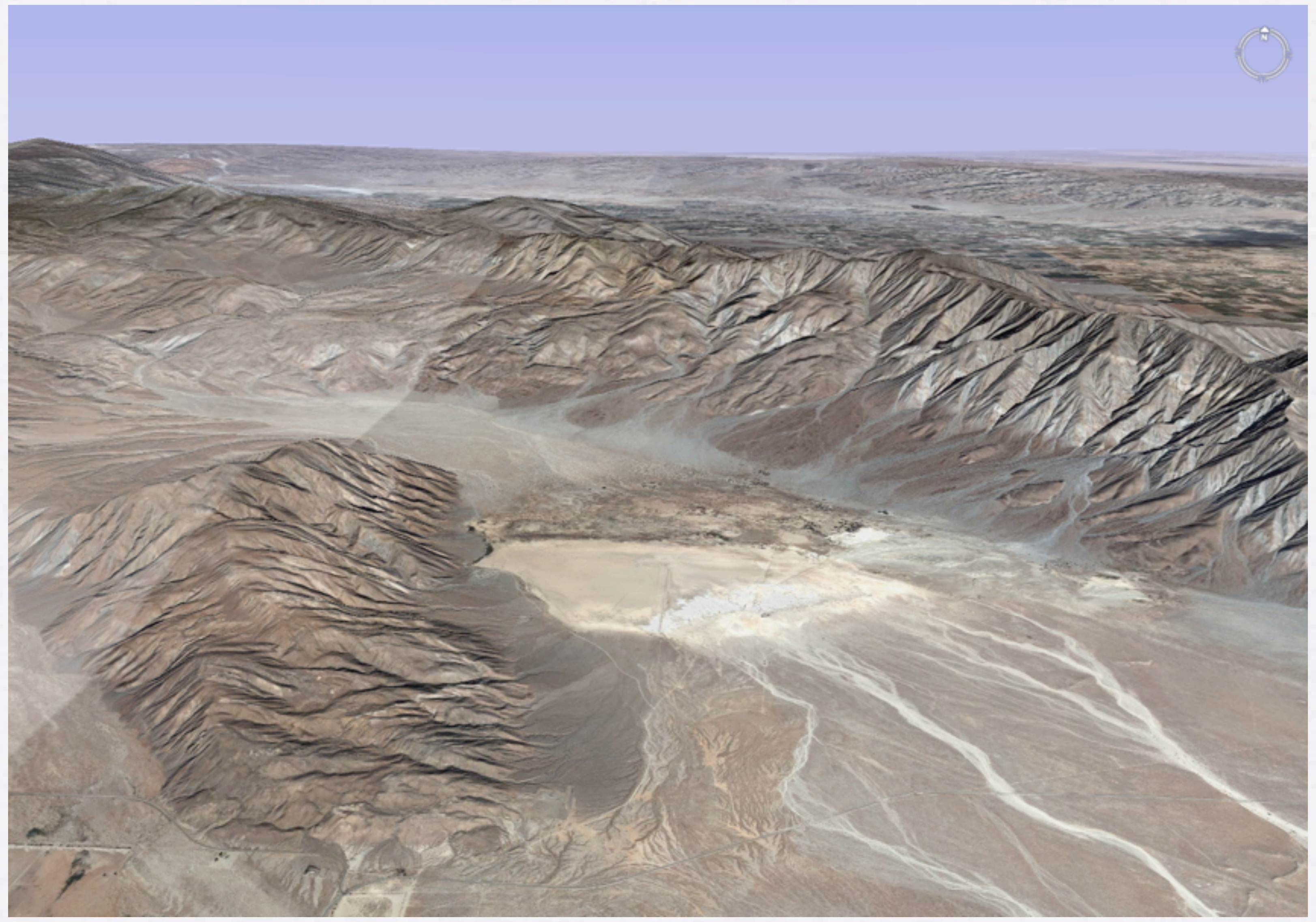
Ionization increases with altitude, as does mean free path, so at 80—100 km the conductive ionosphere forms. Electrons now spiral around **B** for a few orbits before colliding.

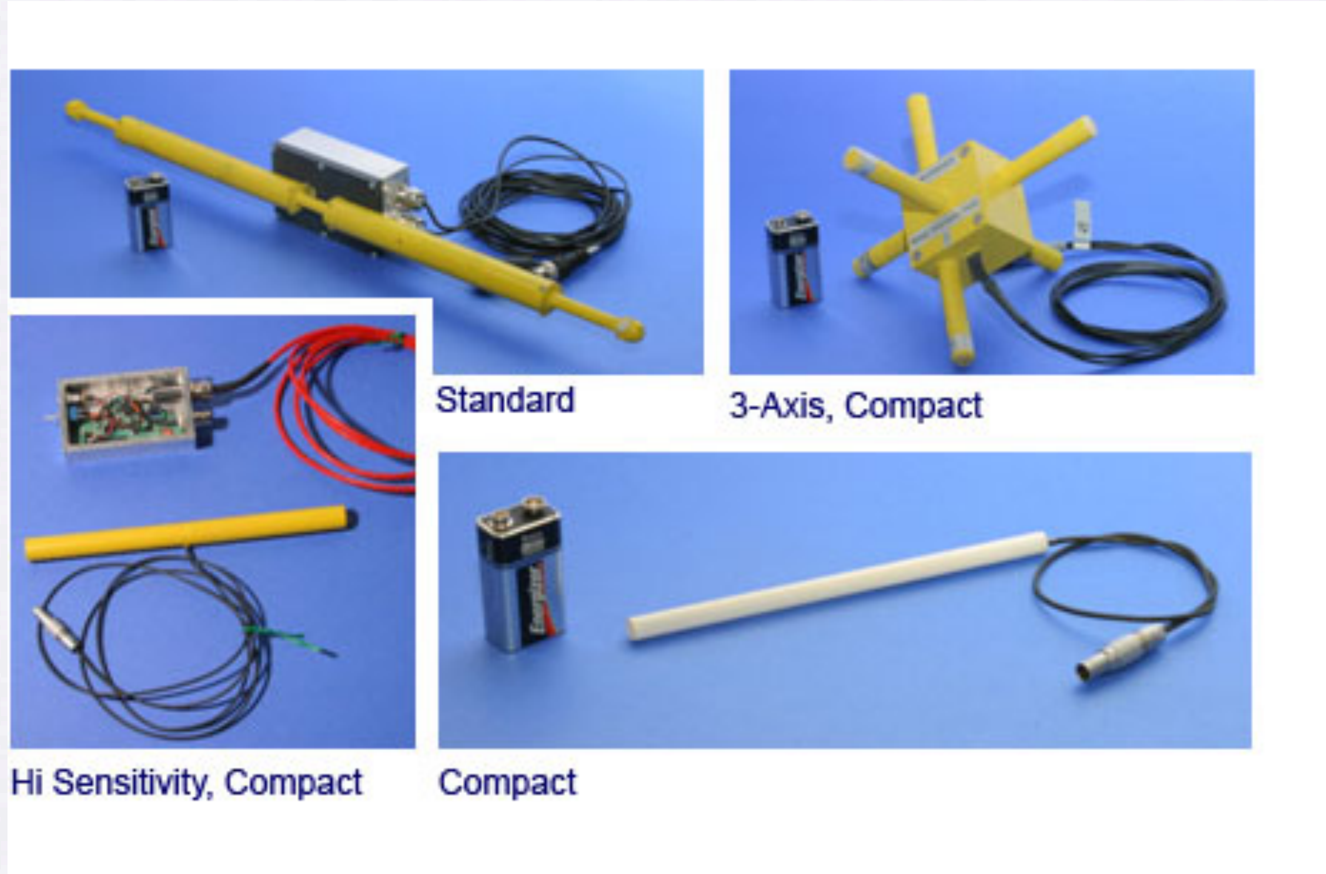


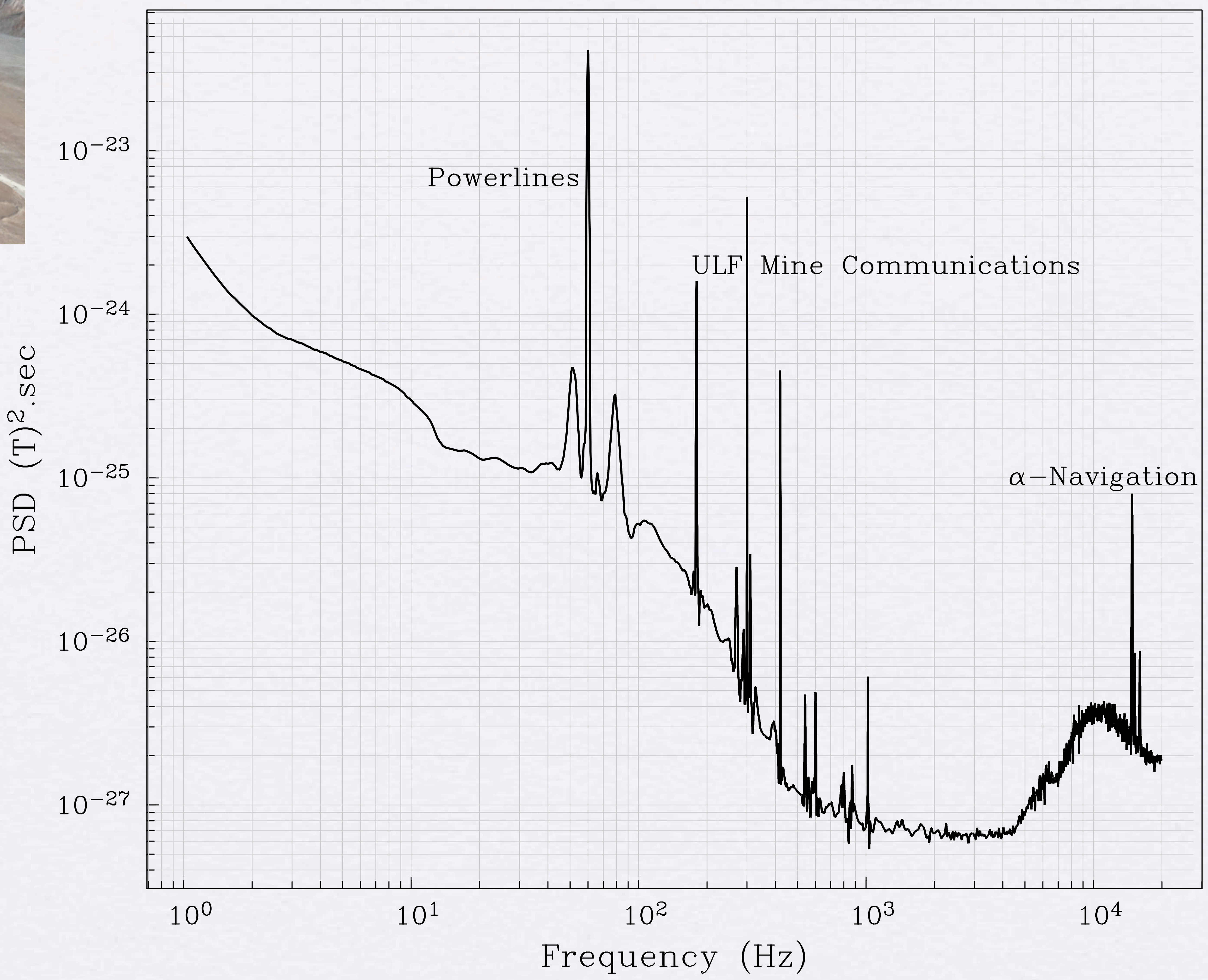
Magnetic field at Clark Dry Lake, courtesy Tom Nielson. The 8 Hz Schumann resonance, powerline noise, and ULF communication signals can be clearly seen.



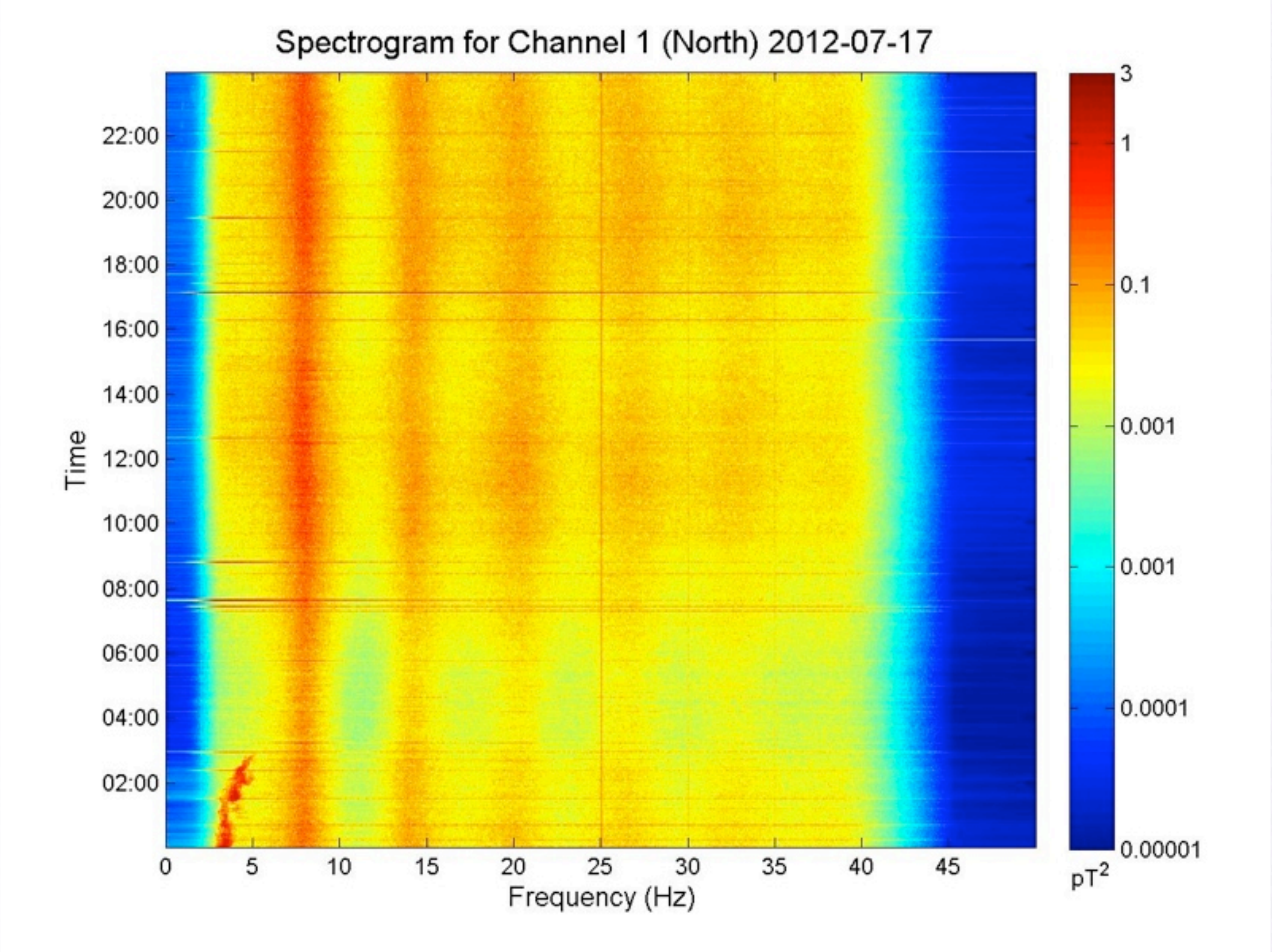
Clark Dry Lake

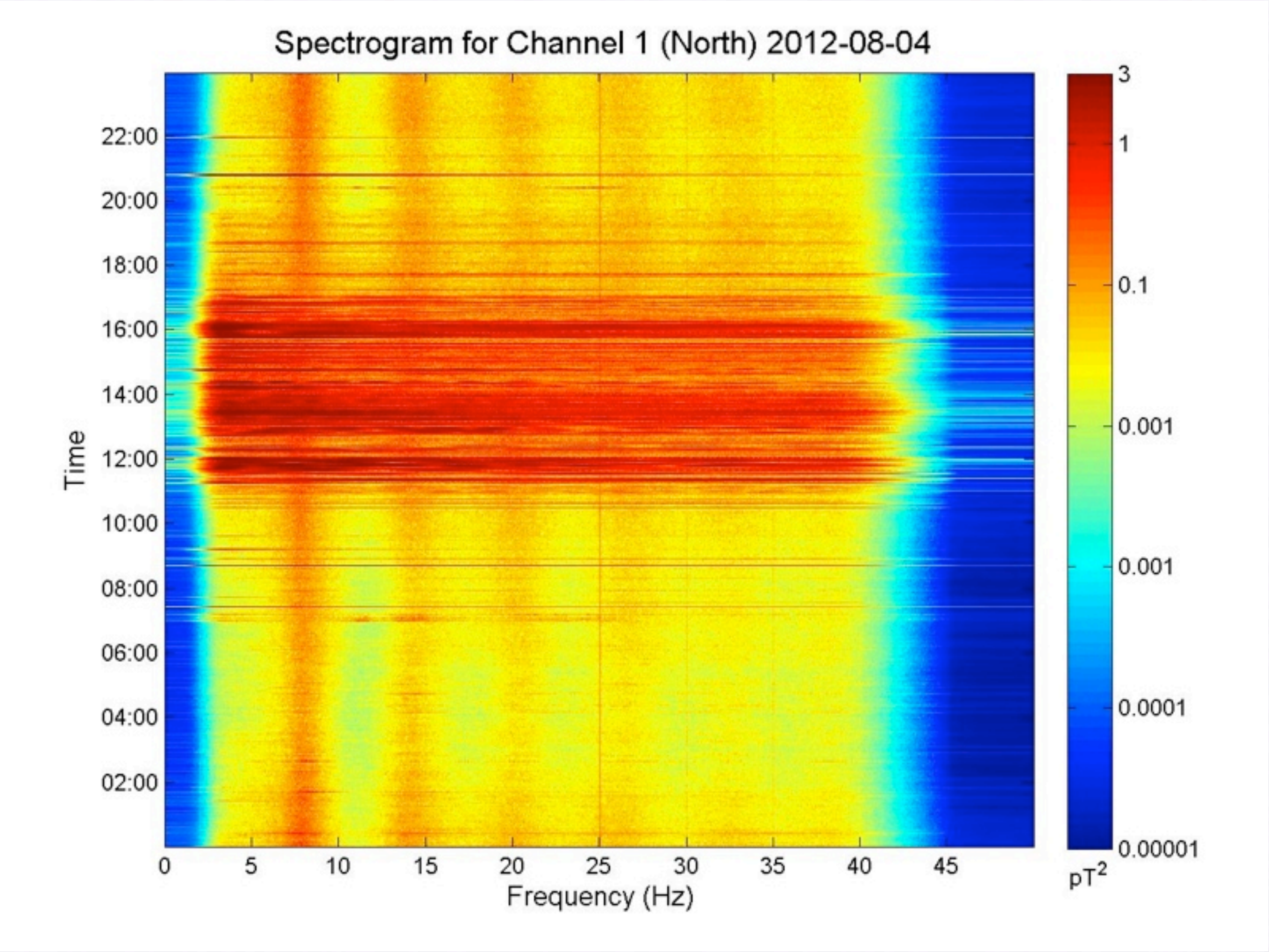


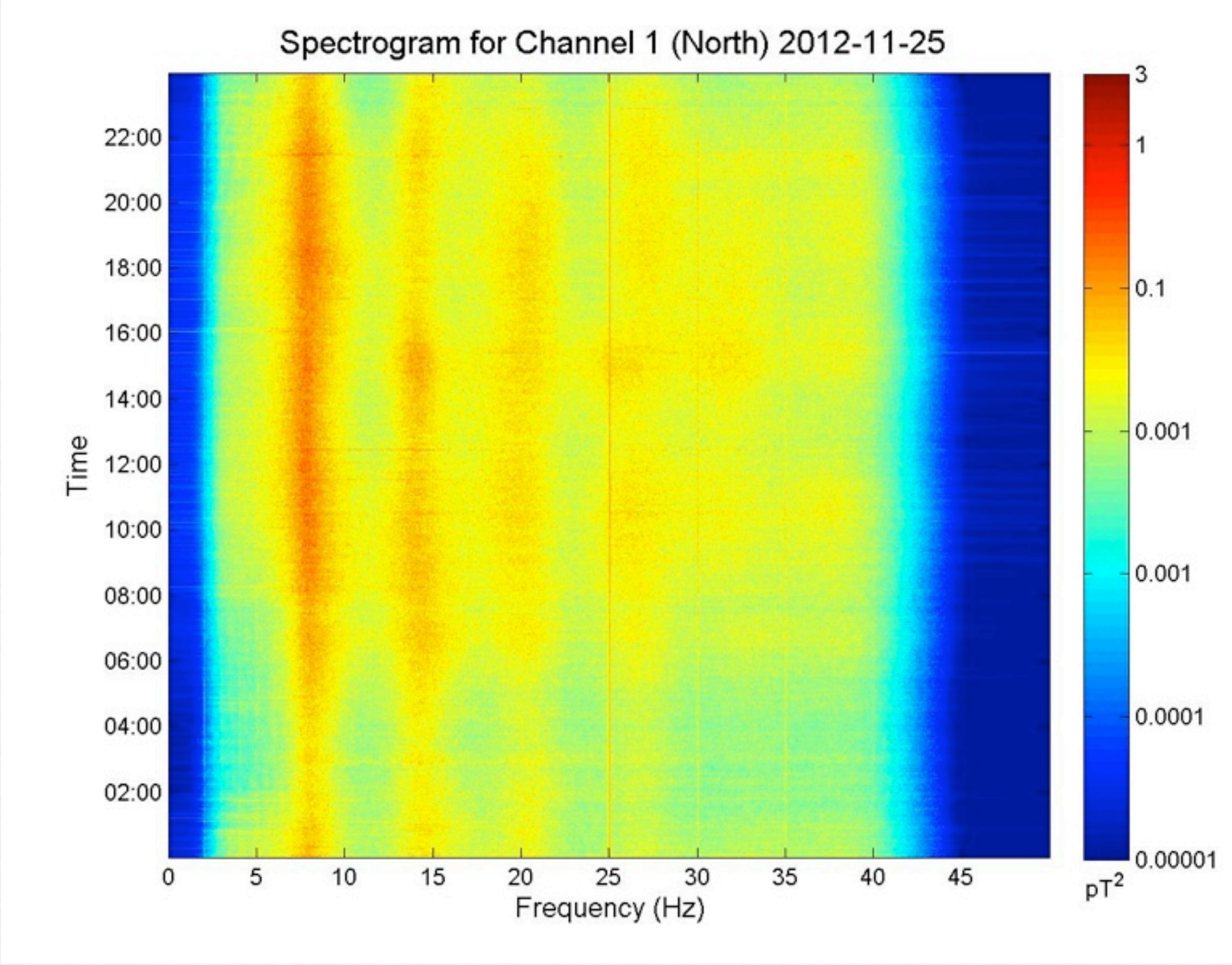




Spectrograms 0-45 Hz
Eskdalemuir Horizontal Induction Coils





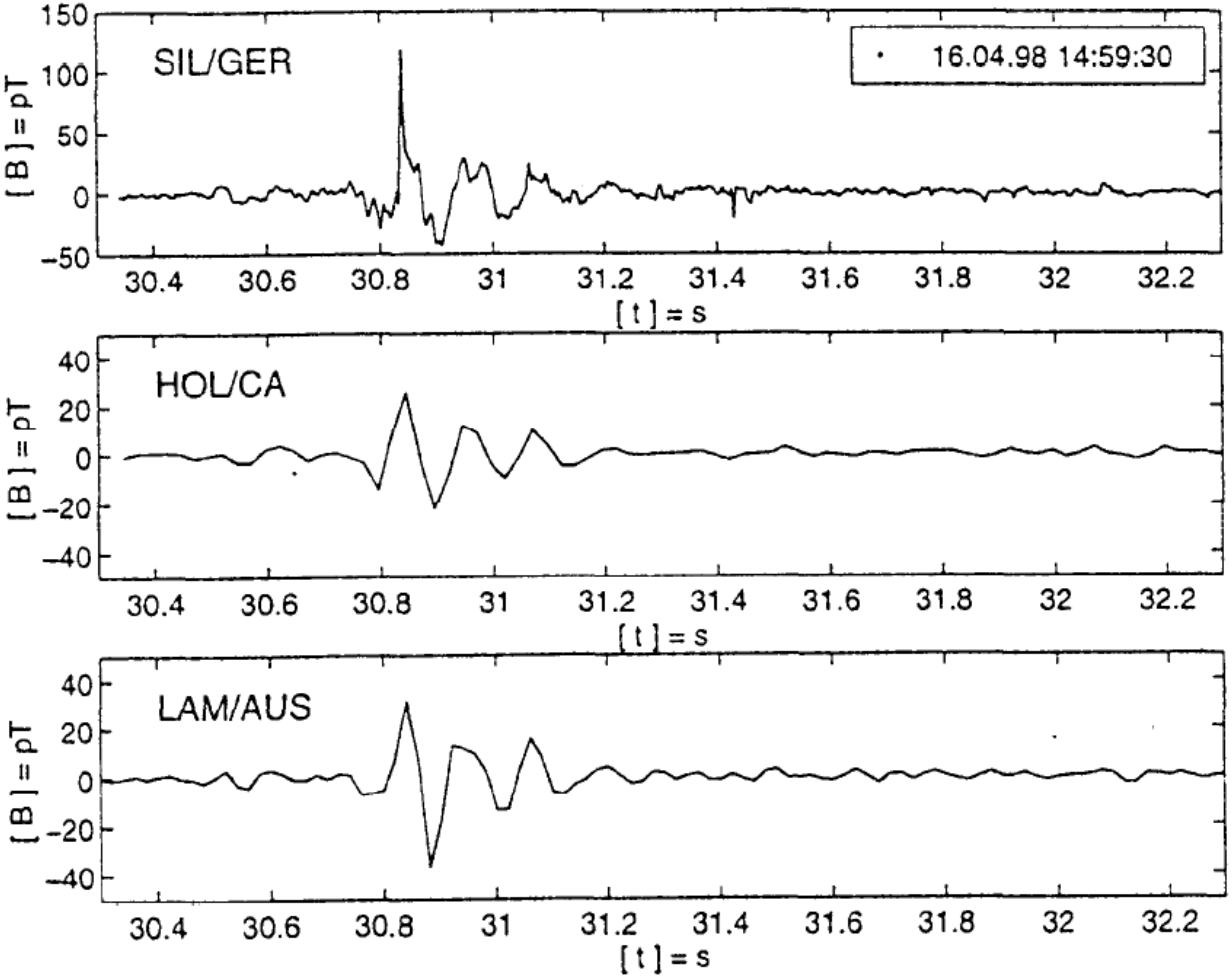


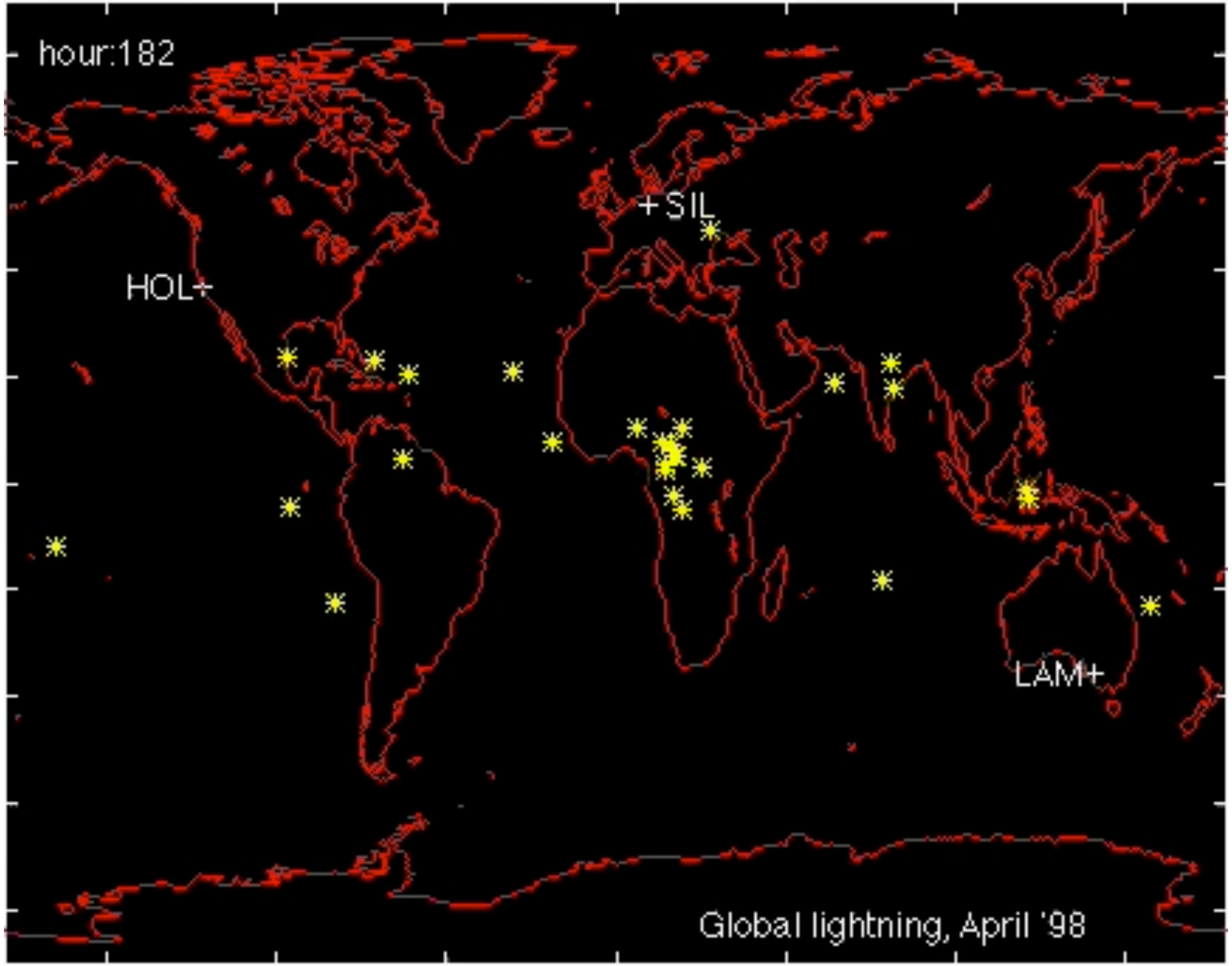
Pc1 pulsations 0:00-3:00, strong summer Schumann resonance

Local afternoon lightning

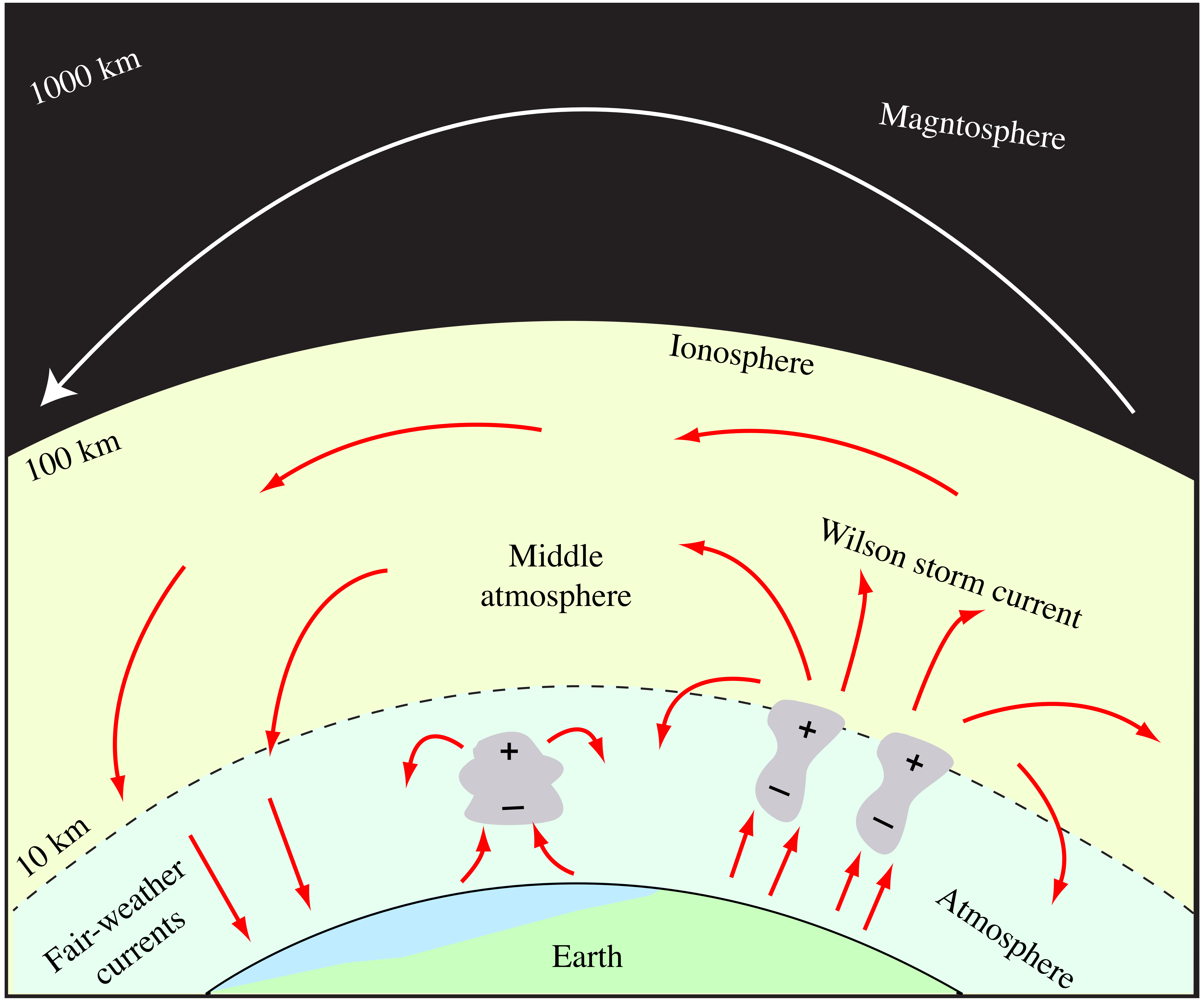
Weaker Schumann resonance in Fall

Cieran Beggan, pers. comm.

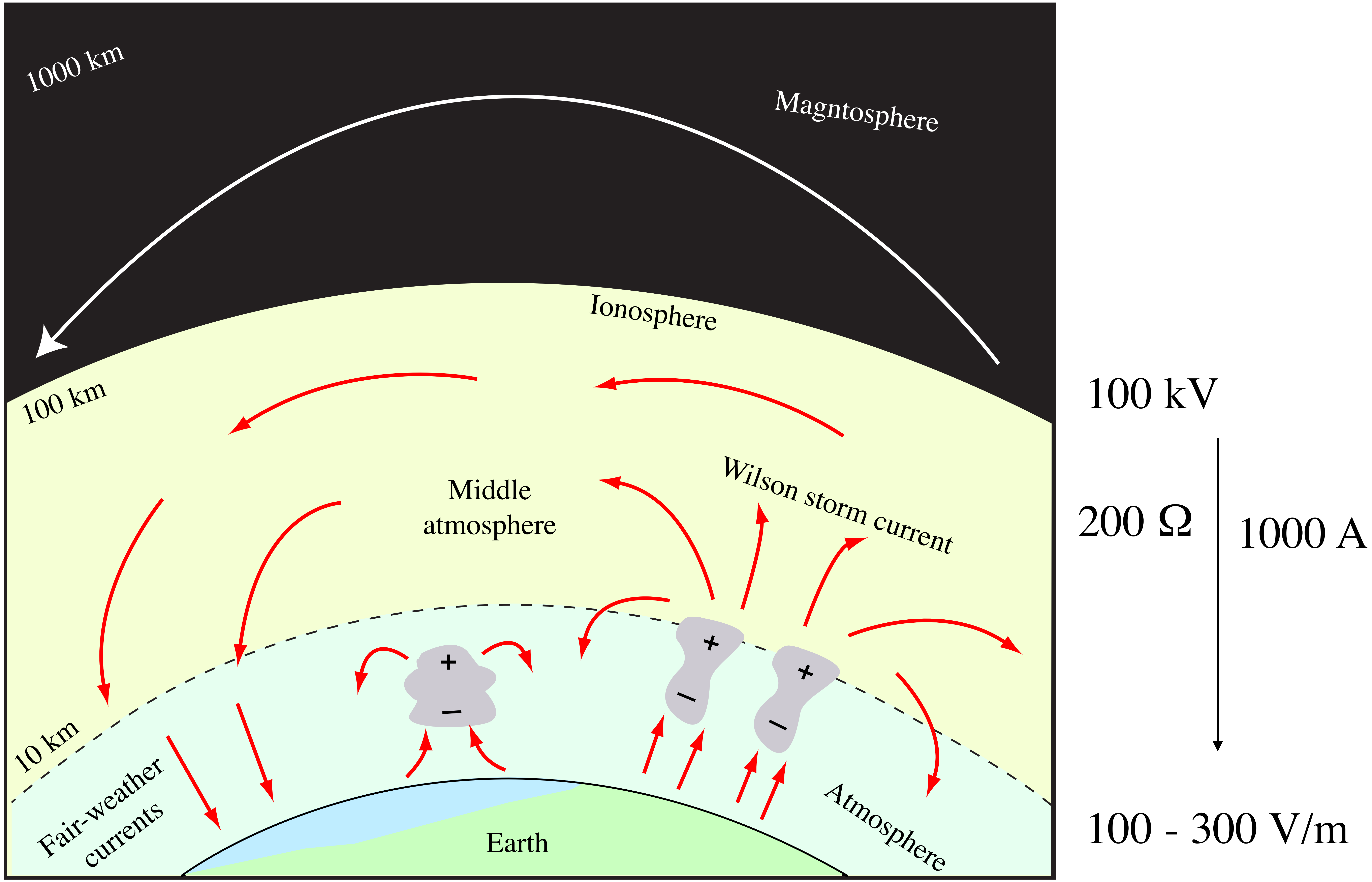

SIL/GER
16.04.98 14:59:30
[B] = pT
[t] = s
HOL/CA
LAM/AUS


hour:182
+SIL
HOL+
LAM+
Global lightning, April '98

Lightning excites the atmosphere cavity, creating resonances and charging the ionosphere with respect to Earth.

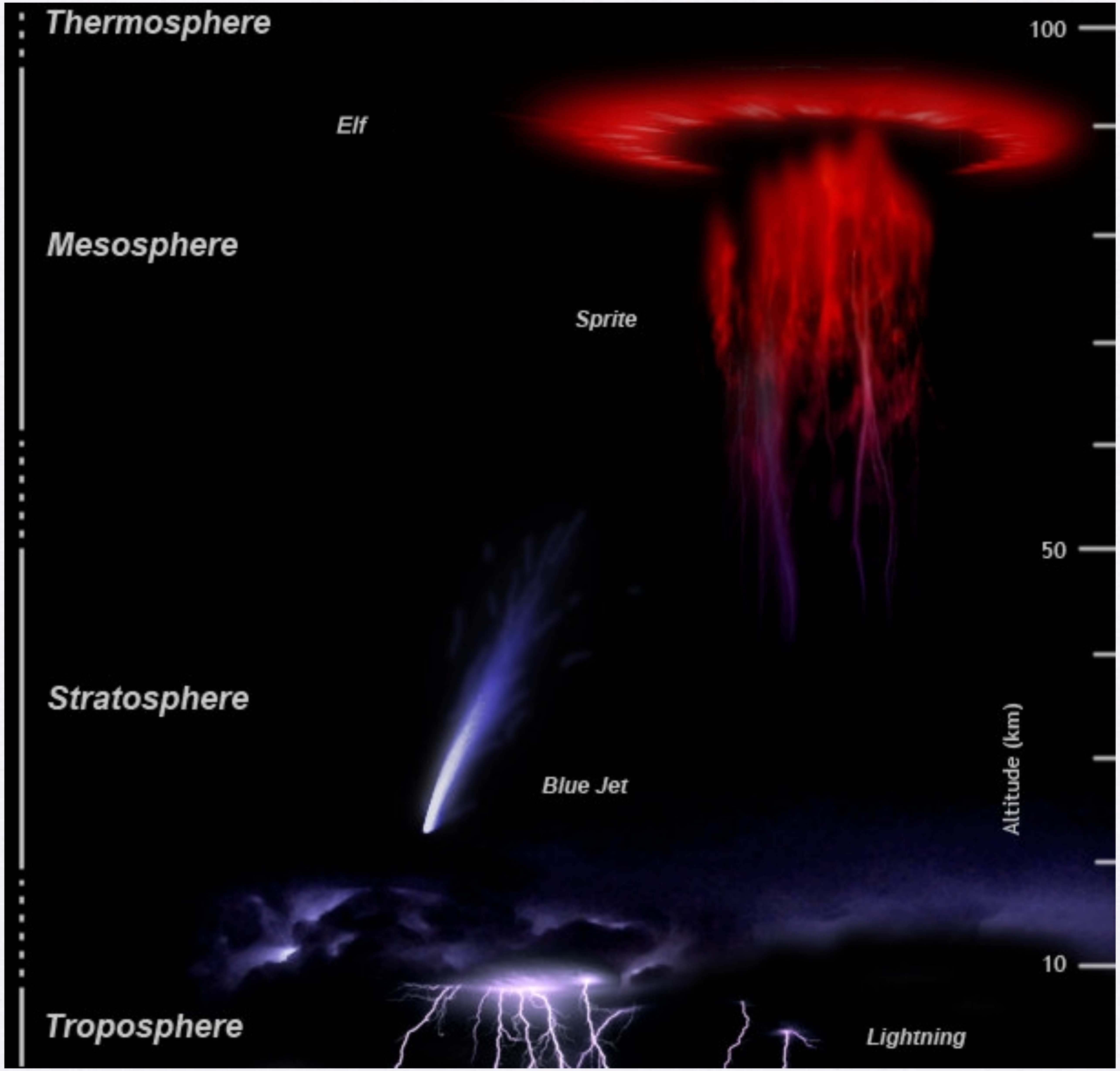


Earth/atmosphere/ionosphere is a capacitor about 1 farad and a t.c. of ~1,000s



Transient Luminous Events

(aka Upper Atmospheric /Ionospheric Lightning)



STEVE

From Wikipedia, the free encyclopedia

For other uses, see Steve (disambiguation).

A photograph of a STEVE phenomenon on 17 August 2015 at Little Bow Resort, AB, Canada

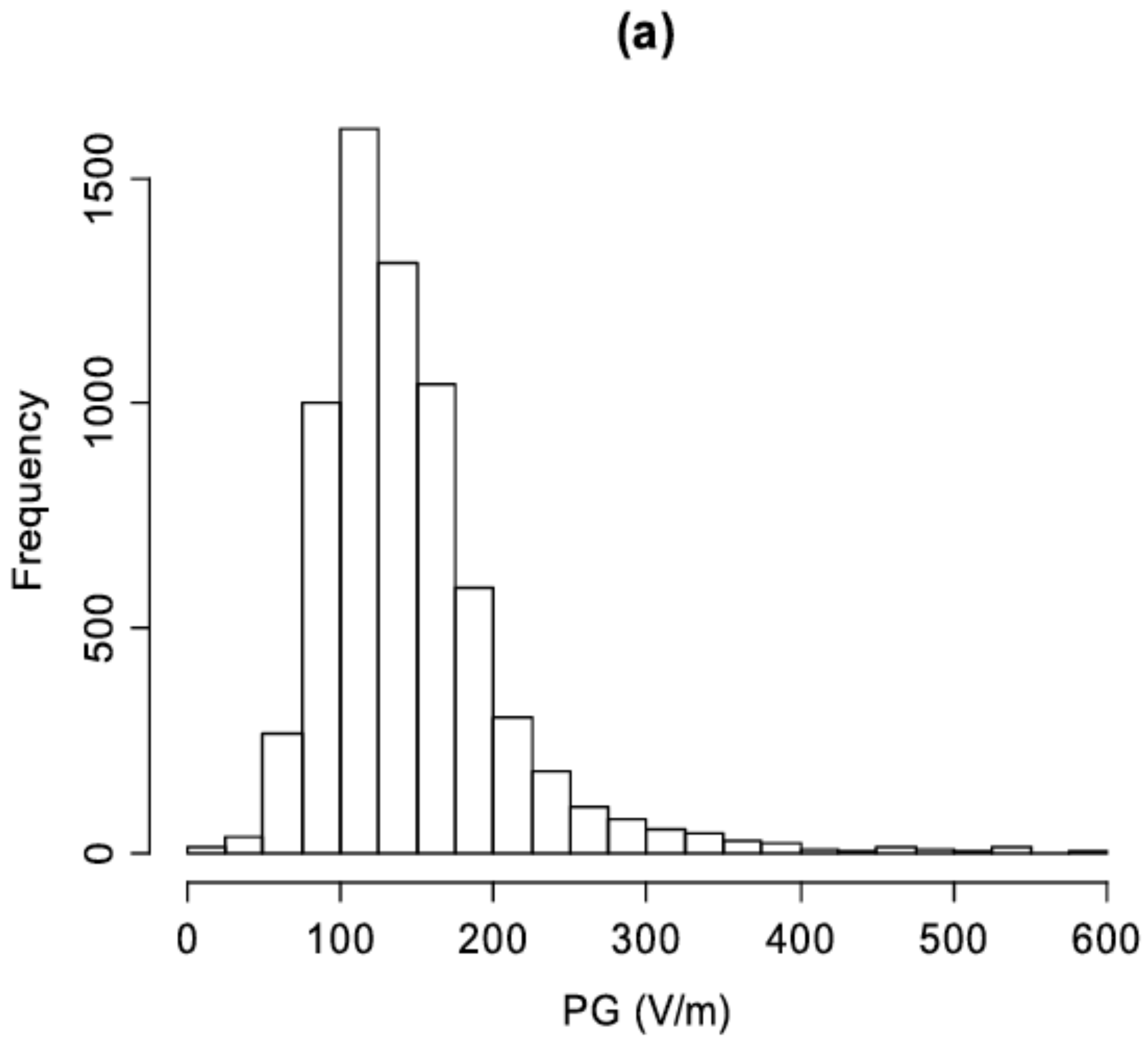
STEVE ("**Strong Thermal Emission Velocity Enhancement**") is an atmospheric optical phenomenon that appears as a purple and green light ribbon in the sky, named in late 2016 by aurora watchers from Alberta, Canada. According to analysis of satellite data from the European Space Agency's Swarm mission, the phenomenon is caused by a 25 km (16 mi) wide ribbon of hot plasma at an altitude of 450 km (280 mi), with a temperature of 3,000 °C (3,270 K; 5,430 °F) and flowing at a speed of 6 km/s (3.7 mi/s) (compared to 10 m/s (33 ft/s) outside the ribbon). The phenomenon is not rare, but had not been investigated and described scientifically prior to that time.[1][2][3]

Contents [hide]

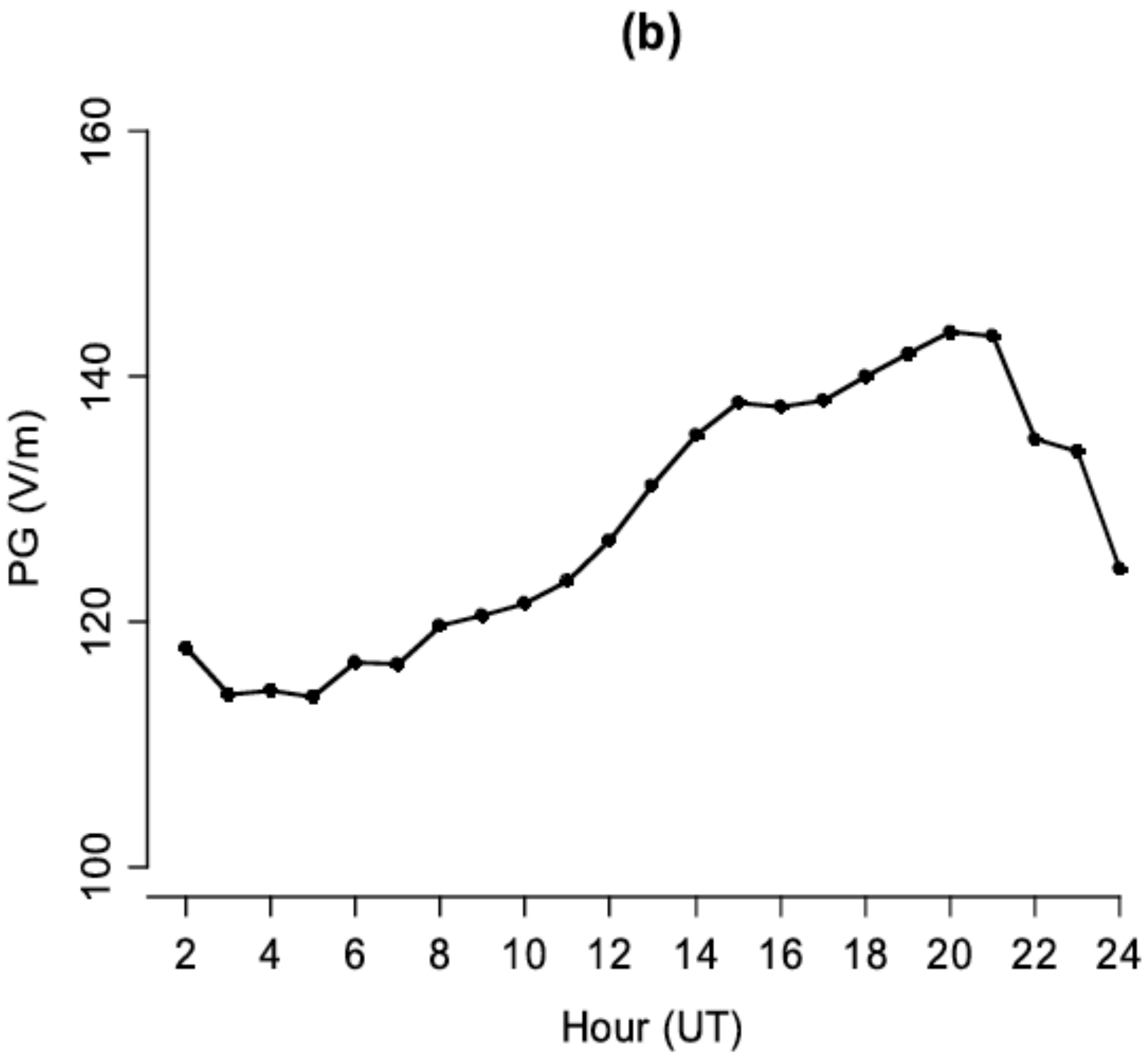
1 Discovery and naming
2 Occurrence and cause
2.1 Association with picket-fence aurora
3 See also
4 References
5 External links

Discovery and naming [edit]

The STEVE phenomenon has been observed by auroral photographers for decades.[3] Some evidence to suggests that observations of it may have been recorded as early as 1705.[4] Notations resembling the phenomenon exist in some observations by Carl Størmer.[5][6]



Carnegie data, 1915-1929.

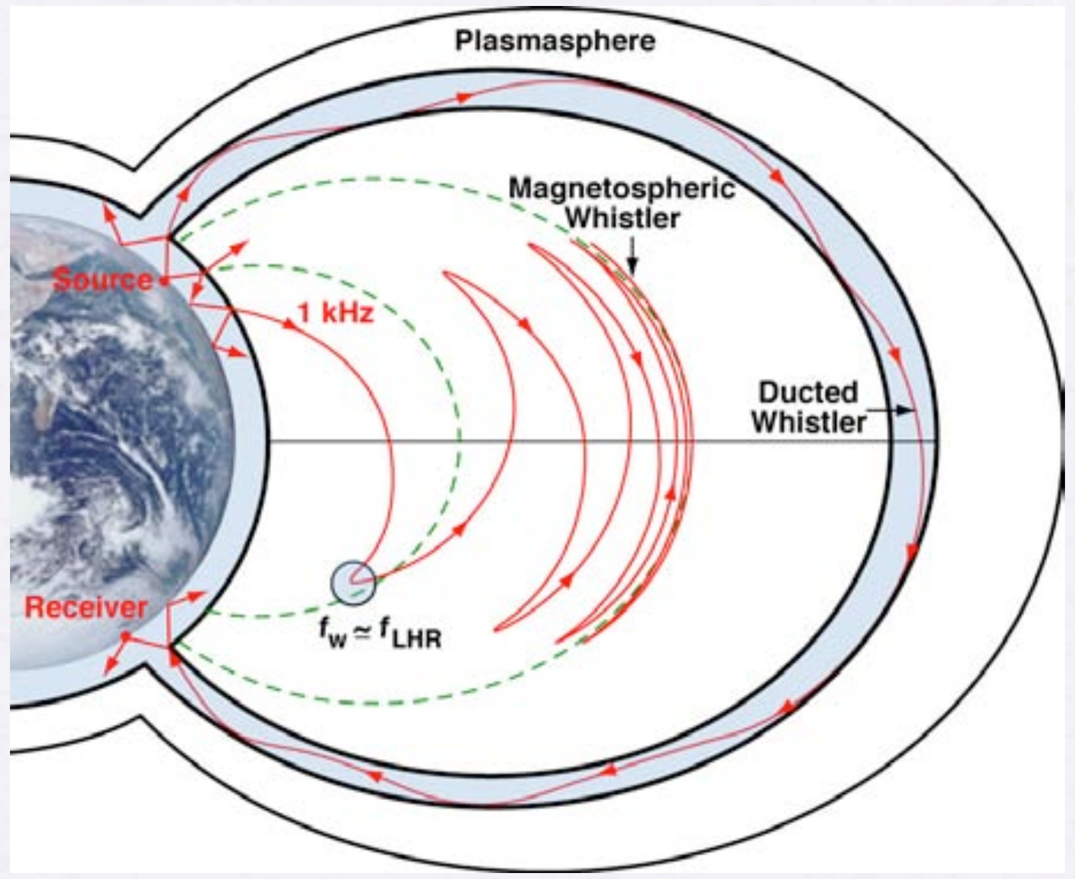


Carnegie curve.

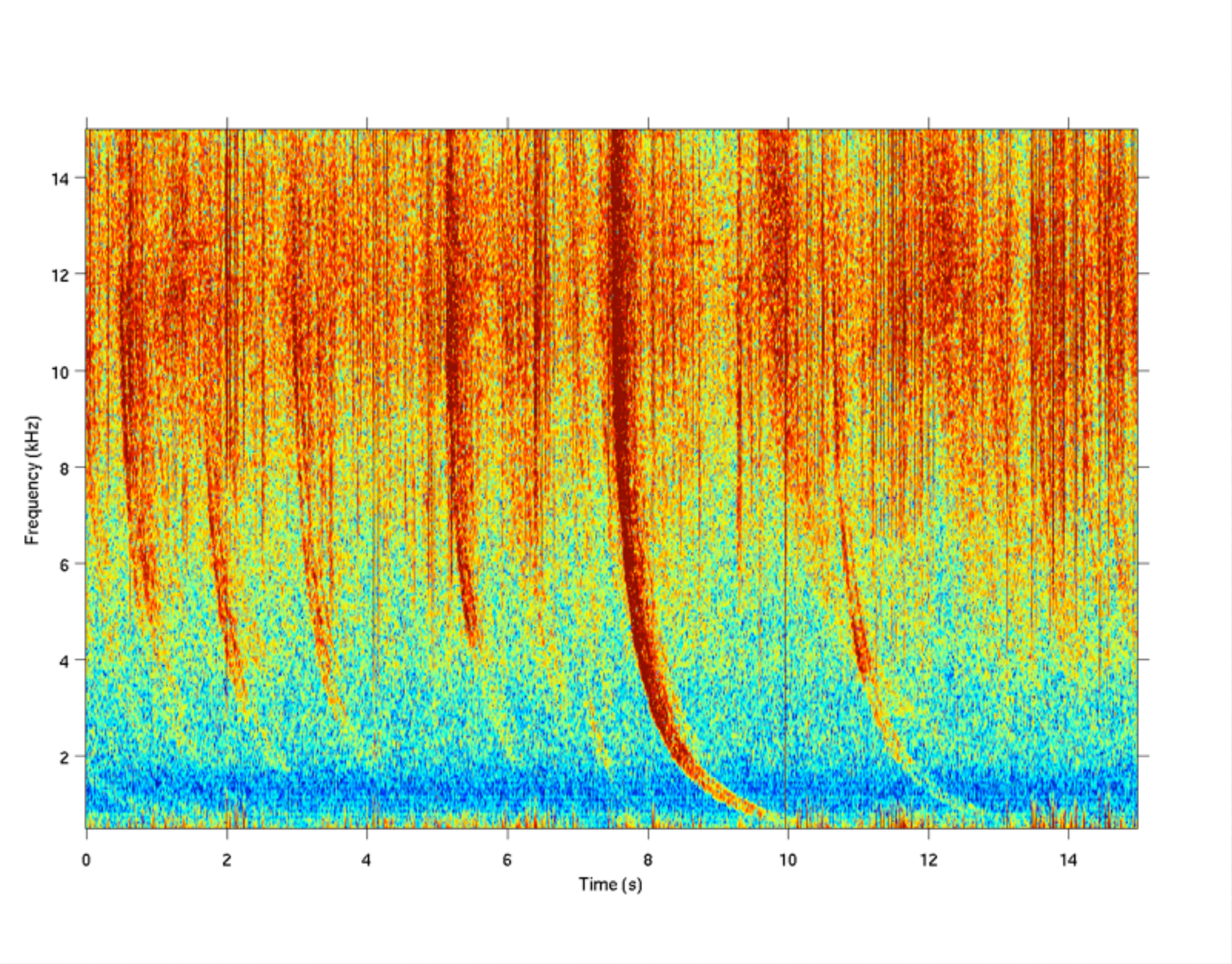
Observations >1Hz

- Pc1 MS Pulsations up to ~0.2 -5Hz
- Ionospheric Alfvén Resonances ~0.5-10Hz
- ELF Sferics 3Hz- 3kHz
- Schumann Resonances - lightning and Transient Luminous Events (TLES) - ~8 Hz and harmonics
- MS Plasmaspheric Hiss ~200Hz - 2kHz
- MS Whistlers & Chorus

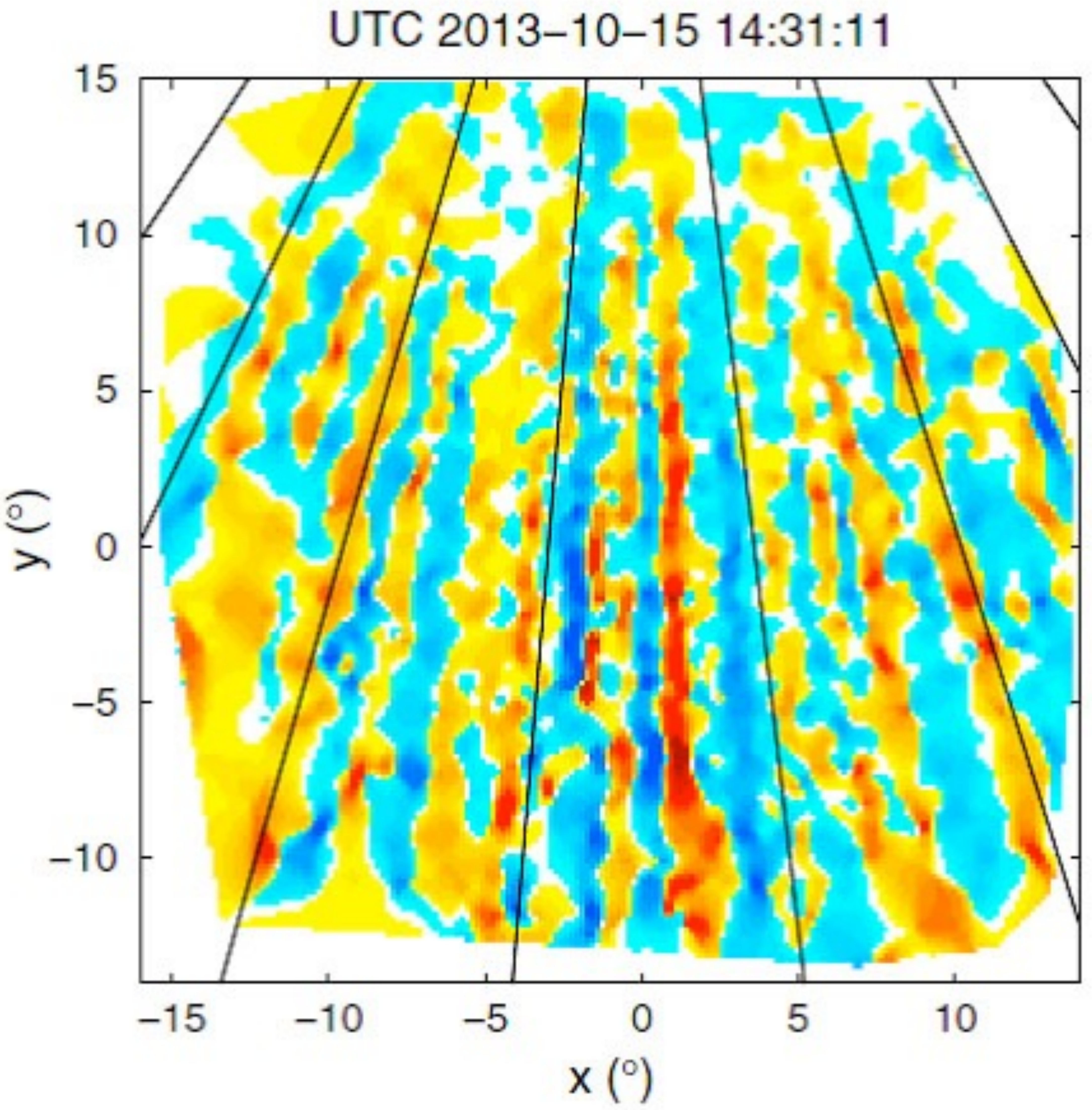
Whistlers



- Lightning couples through ionosphere into magnetosphere
- travel through ducts or not
- important contributors to energetic electron scattering in the slot region of the radiation belts



Magnetic flux tubes at an altitude of 600 km. Black lines are field lines.

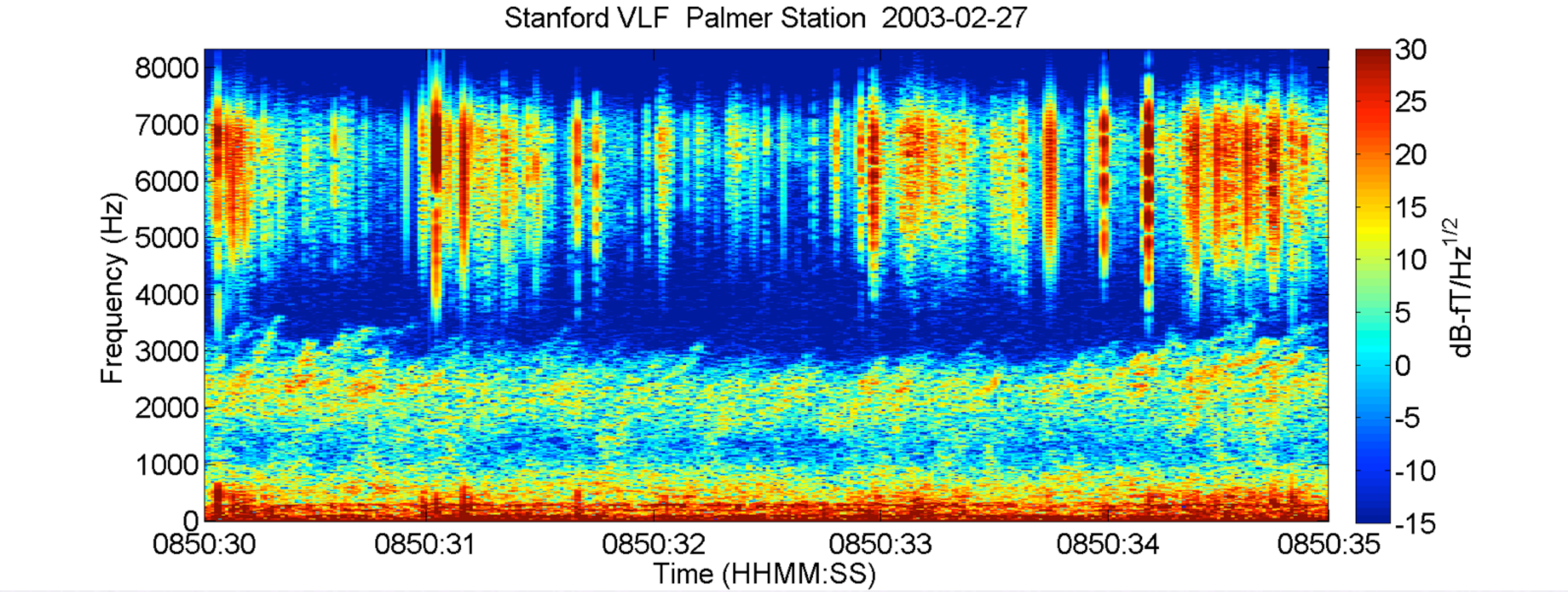


S. T. Loi et al., 2015, *Geophys. Res. Lett.* doi:10.1002/2015GL063699

Chorus

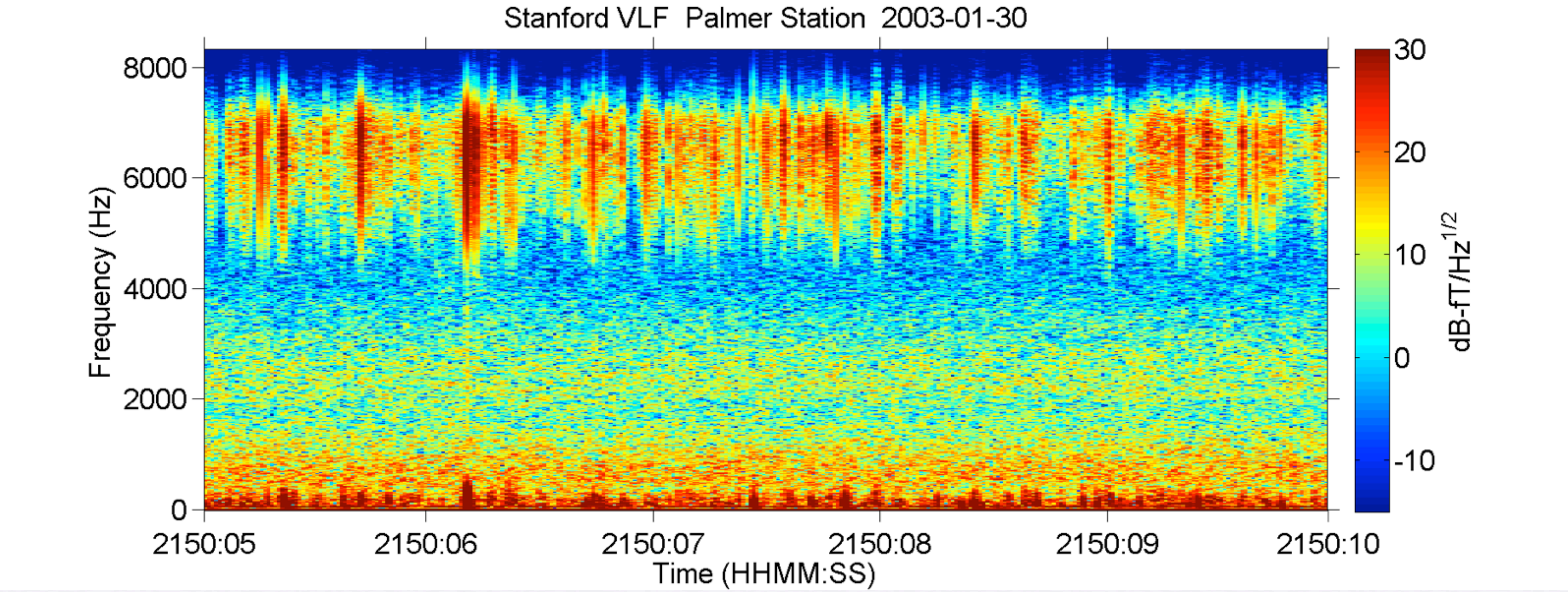
- MS source beyond the plasmasphere - influences acceleration [Baker et al., 2004; Horne et al., 2005; Spasojevic and Inan, 2005] and loss [O'Brien et al., 2004; Inan et al., 1992; Lorentzen et al., 2001] of energetic particles.

- Chorus can evolve into hiss, Bortnik et al.,2008, Nature, from CLUSTER and CRRES observations.



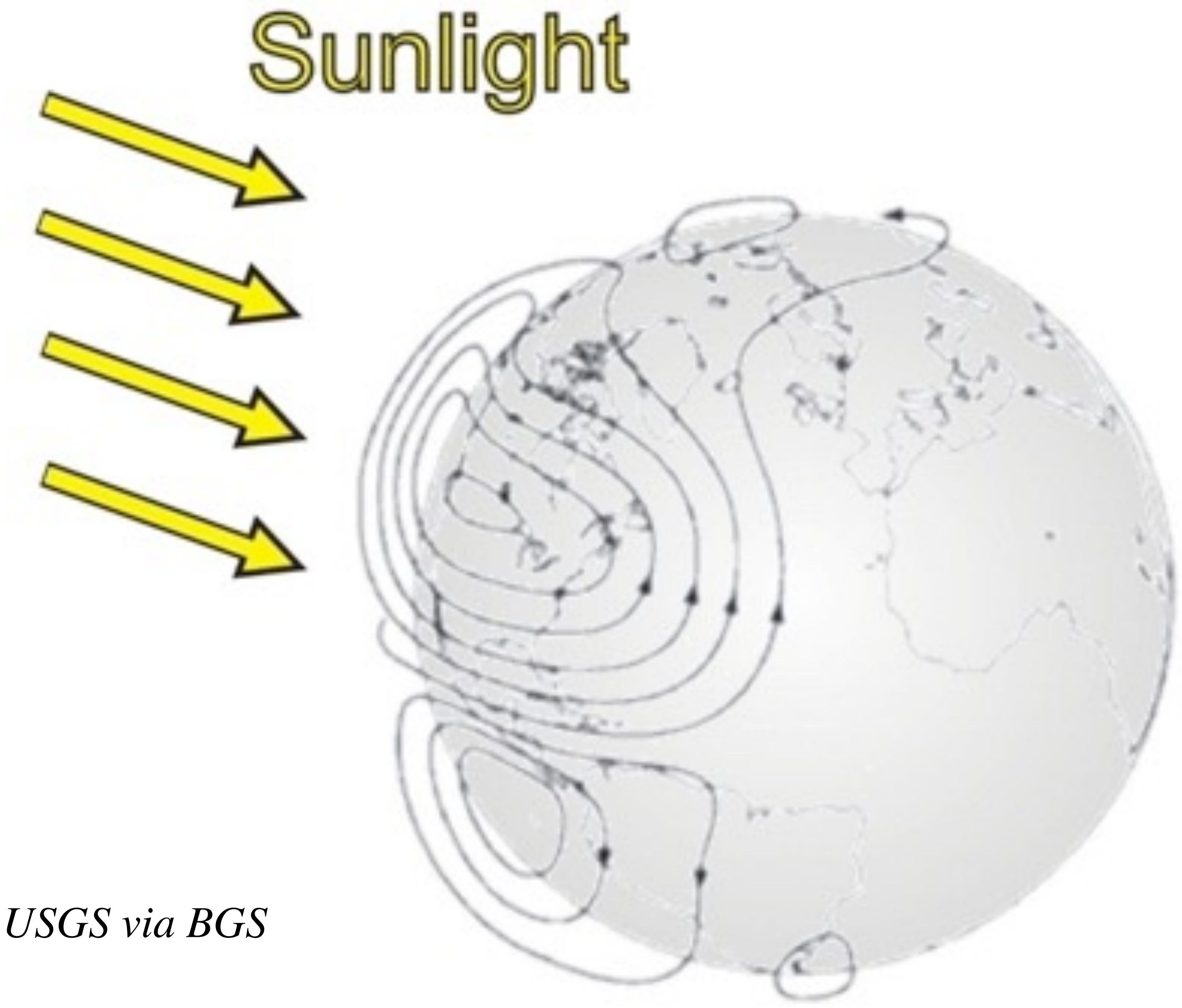
Hiss

Thorne et al, 1973, JGR

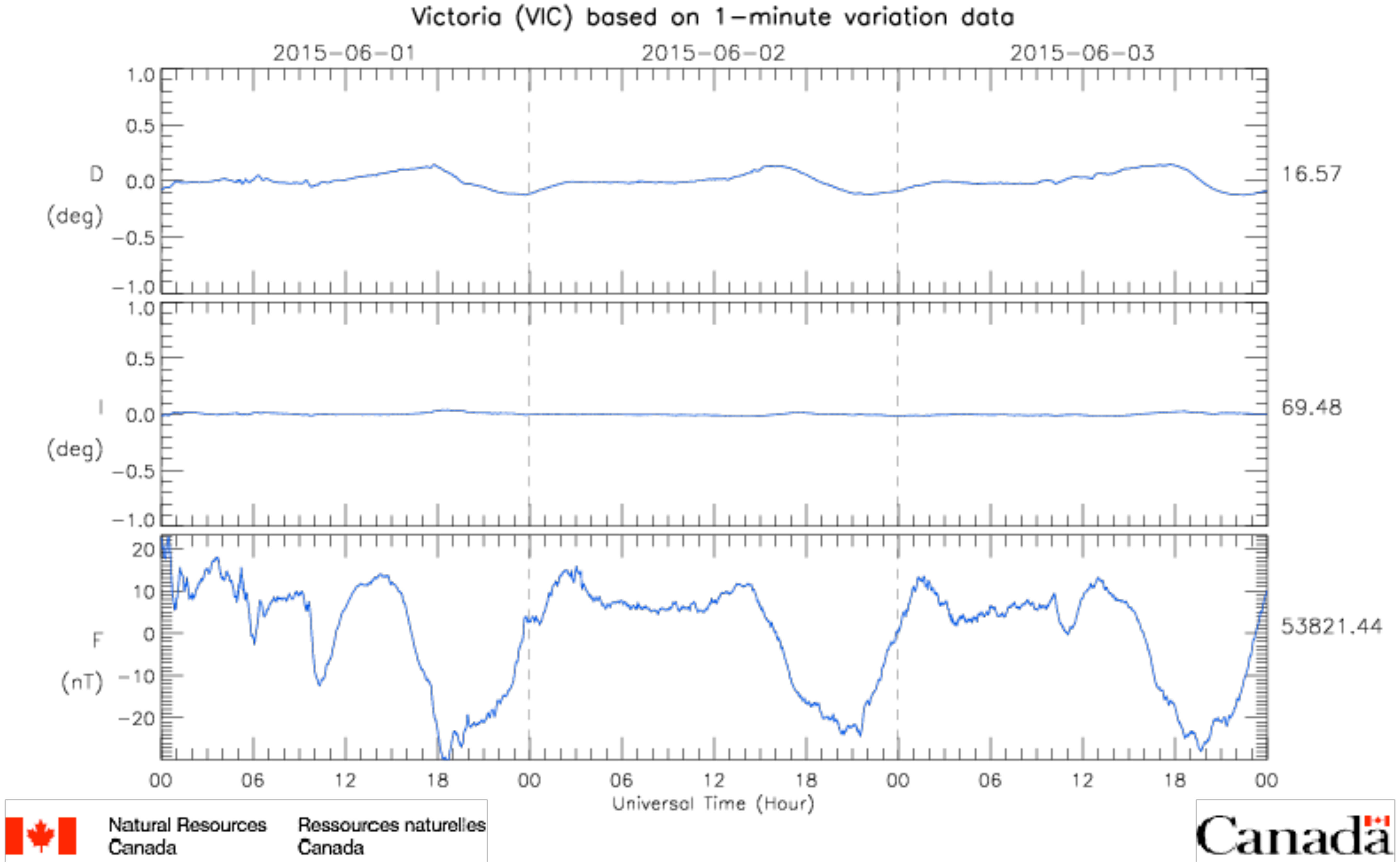


- confined to the plasmasphere
- one of the main scattering agents that maintains the slot region
- origin in chorus/lightning

Thermally induced ionospheric tidal currents are generated on the dayside, and create a daily variation, or *Sq*, in Earth's magnetic field.



USGS via BGS



Conductivity is anisotropic:

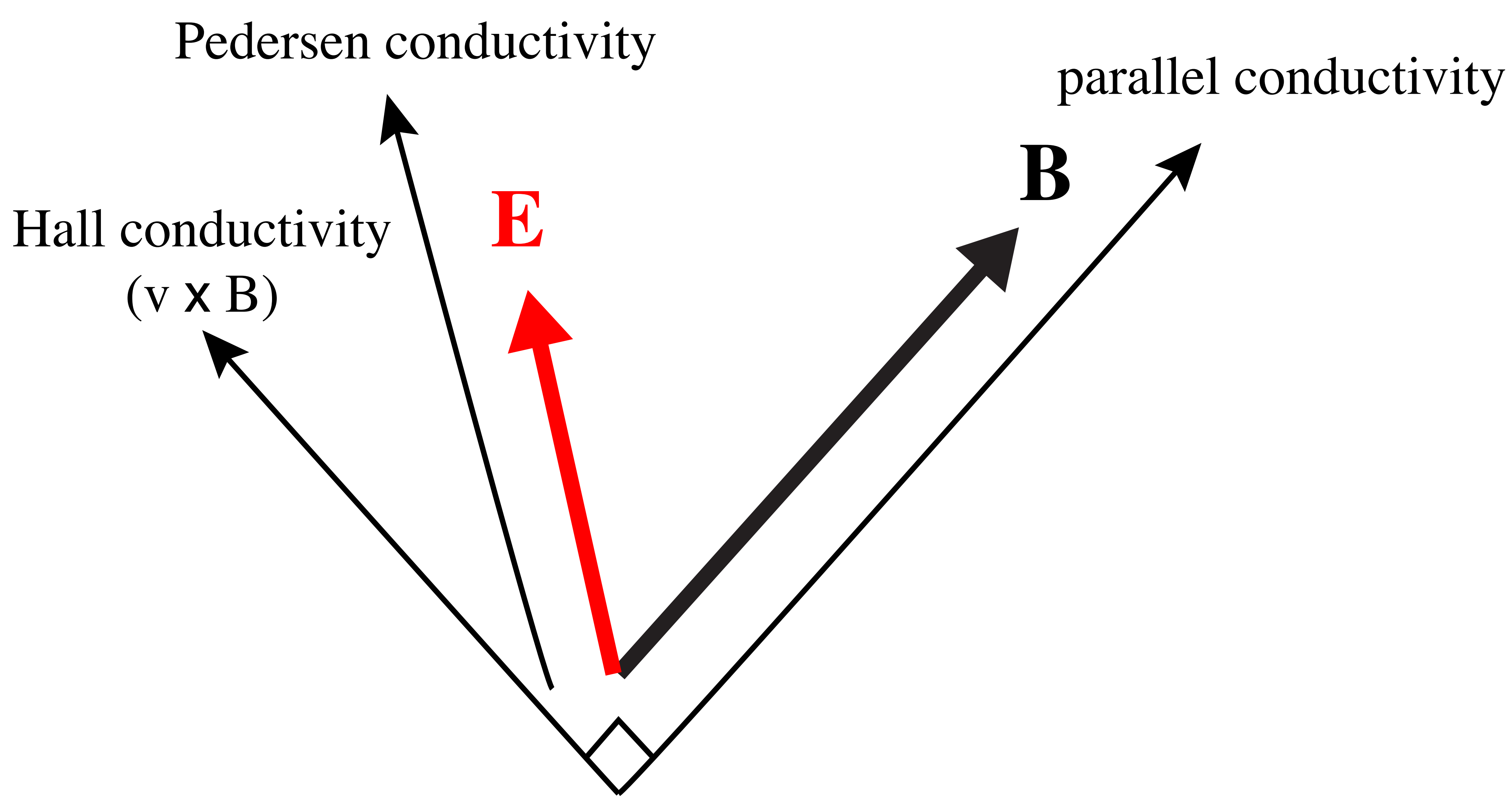
(here **B** is in the z-direction)

$$\mathbf{J} = \begin{bmatrix} \sigma_P & \sigma_H & 0 \\ -\sigma_H & \sigma_P & 0 \\ 0 & 0 & \sigma_{||} \end{bmatrix} (\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

$$\sigma_{||} = Nq^2 \left(\frac{1}{\nu_p m_p} + \frac{1}{\nu_e m_e} \right)$$

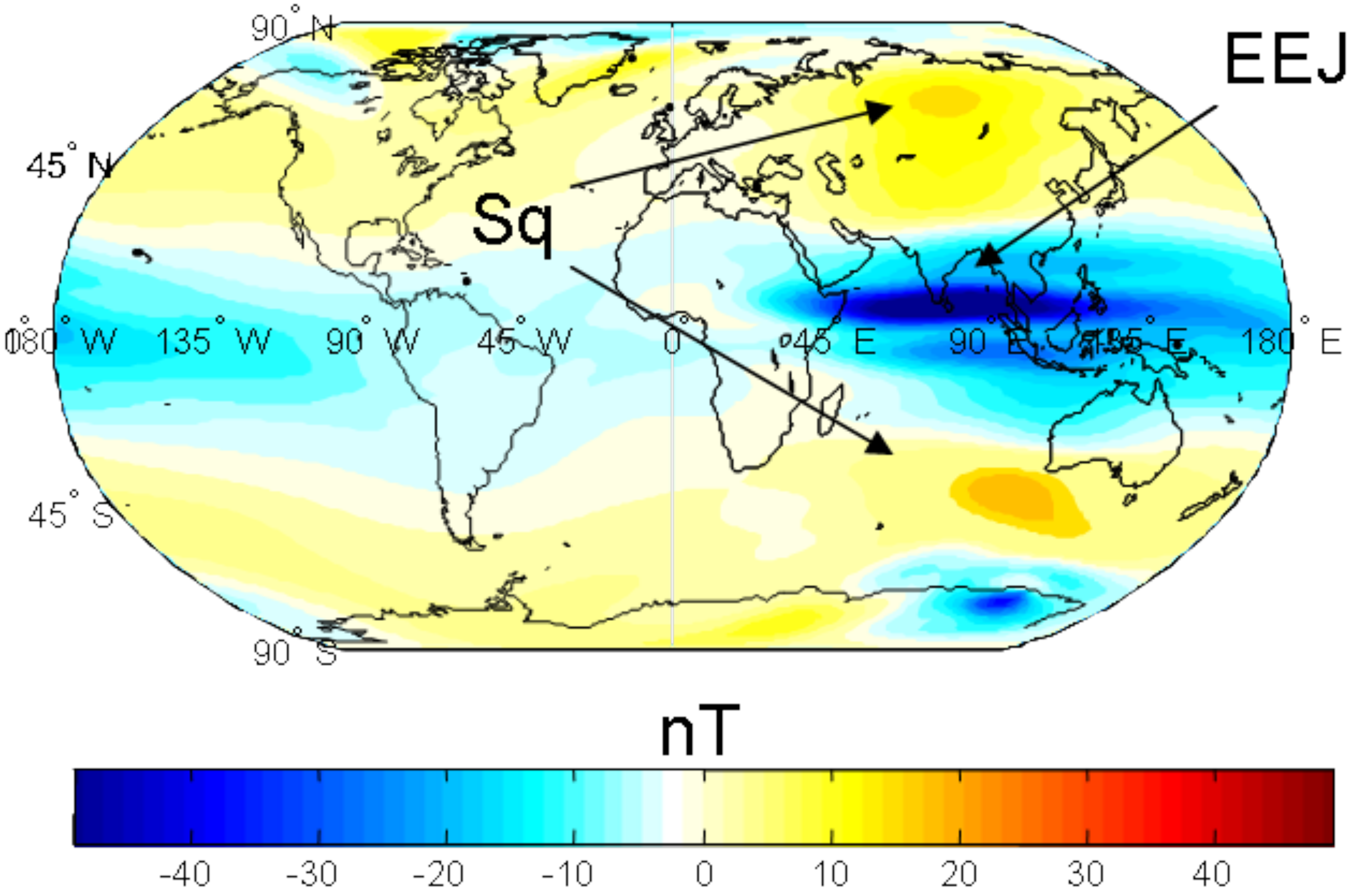
$$\sigma_P = Nq^2 \left(\frac{\nu_p / m_p}{\nu_p^2 + \omega_p^2} + \frac{\nu_e / m_e}{\nu_e^2 + \omega_e^2} \right)$$

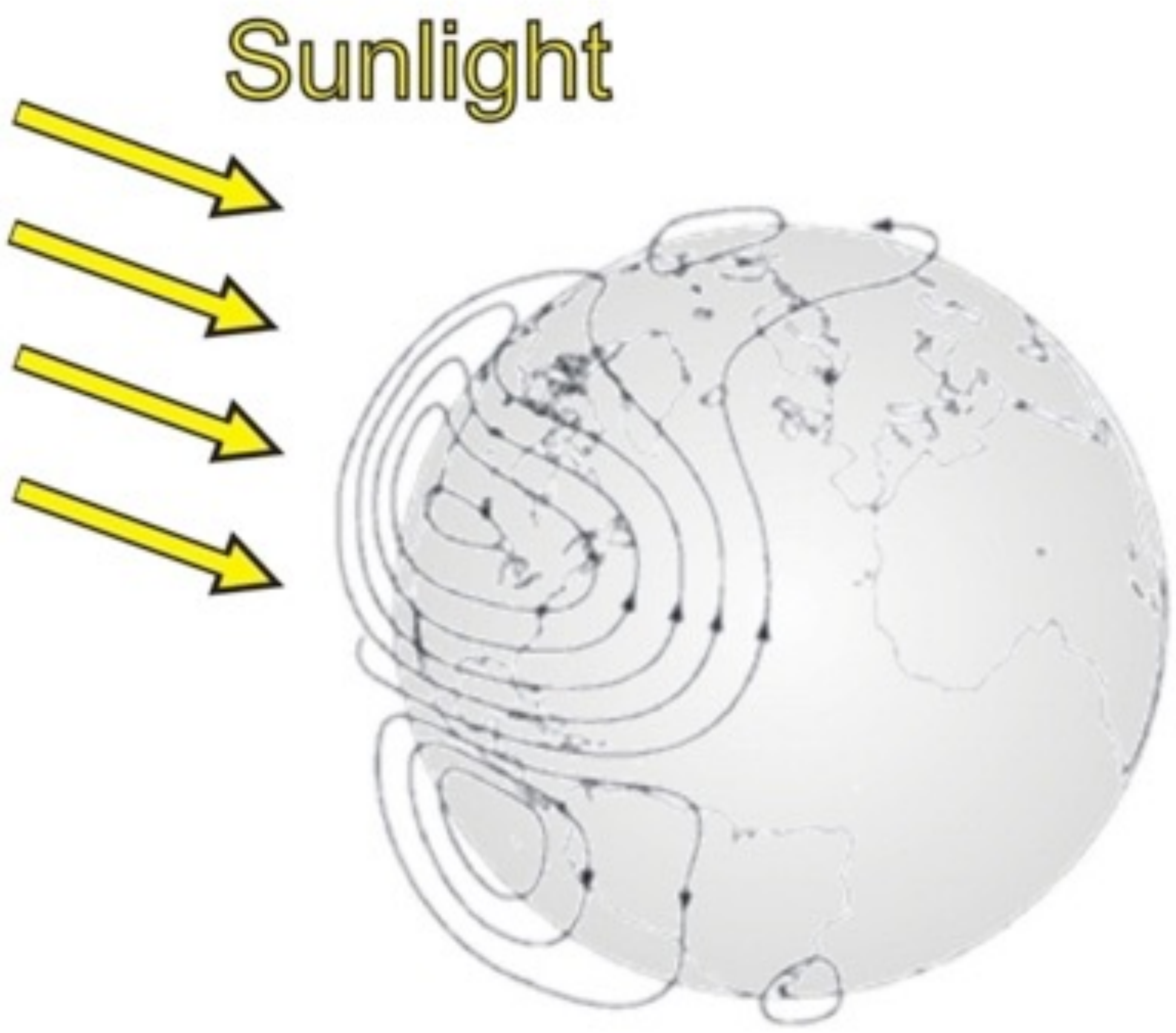
$$\sigma_H = Nq^2 \left(\frac{\omega_p / m_p}{\nu_p^2 + \omega_p^2} + \frac{\omega_e / m_p}{\nu_e^2 + \omega_e^2} \right)$$



Conductivities depend on field strengths, collision frequencies, and cyclotron frequencies.

Hall currents are charges moving perpendicular to both **E** and **B**. At the magnetic equator these currents can flow horizontally, creating the equatorial electrojet.





The K-index measures maximum fluctuation relative to a quiet day during a 3-hour window: