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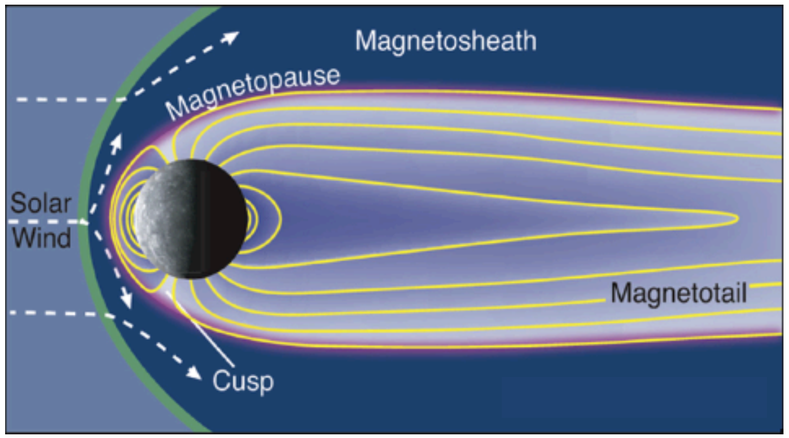
Magnetospheres

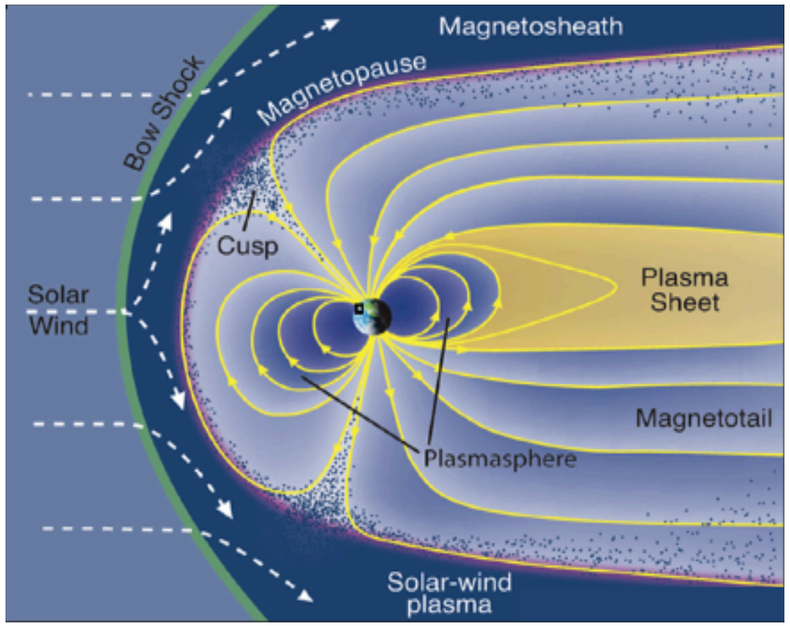
John Coxon

john.coxon@northumbria.ac.uk

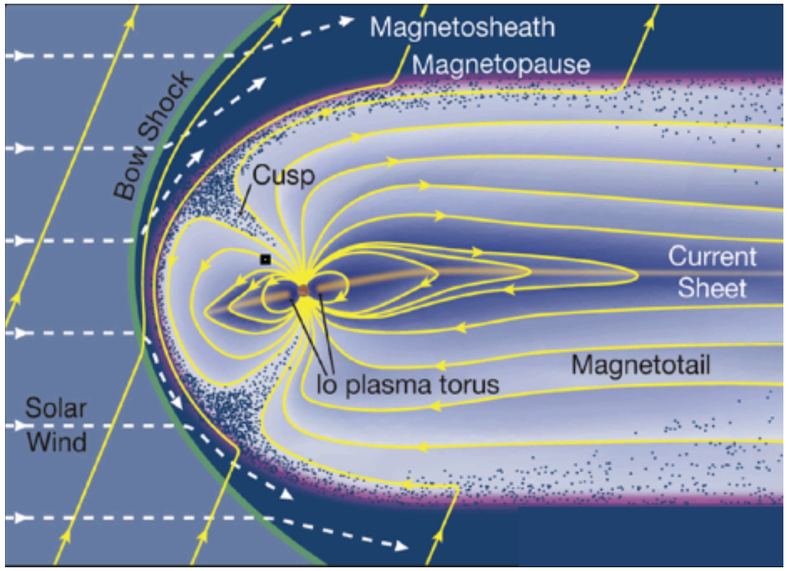
Magnetospheres



Mercury (~400x)



Earth (~40x)



Jupiter (~1x)

Fran Bagenal and Steve Bartlett
john.coxon@northumbria.ac.uk

Magnetospheres

- Why do we see magnetospheres?
- The Dungey Cycle
- Geomagnetic storms and substorms
- Regions
- Populations
- Currents
- Auroras (briefly)

john.coxon@northumbria.ac.uk

Building on previous lectures

- Building on…
  - Introduction to Plasma Physics (Oliver Allanson)
  - MHD: Introduction (Alex Russell)
  - MHD: Waves and Instabilities (Thomas Howton)
  - Magnetic Reconnection (Clare Parnell)
  - CMEs, the Solar Wind and the Heliosphere (Julia Stawarz)

john.coxon@northumbria.ac.uk

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Why do we see magnetospheres?

john.coxon@northumbria.ac.uk

Three types of plasma motion

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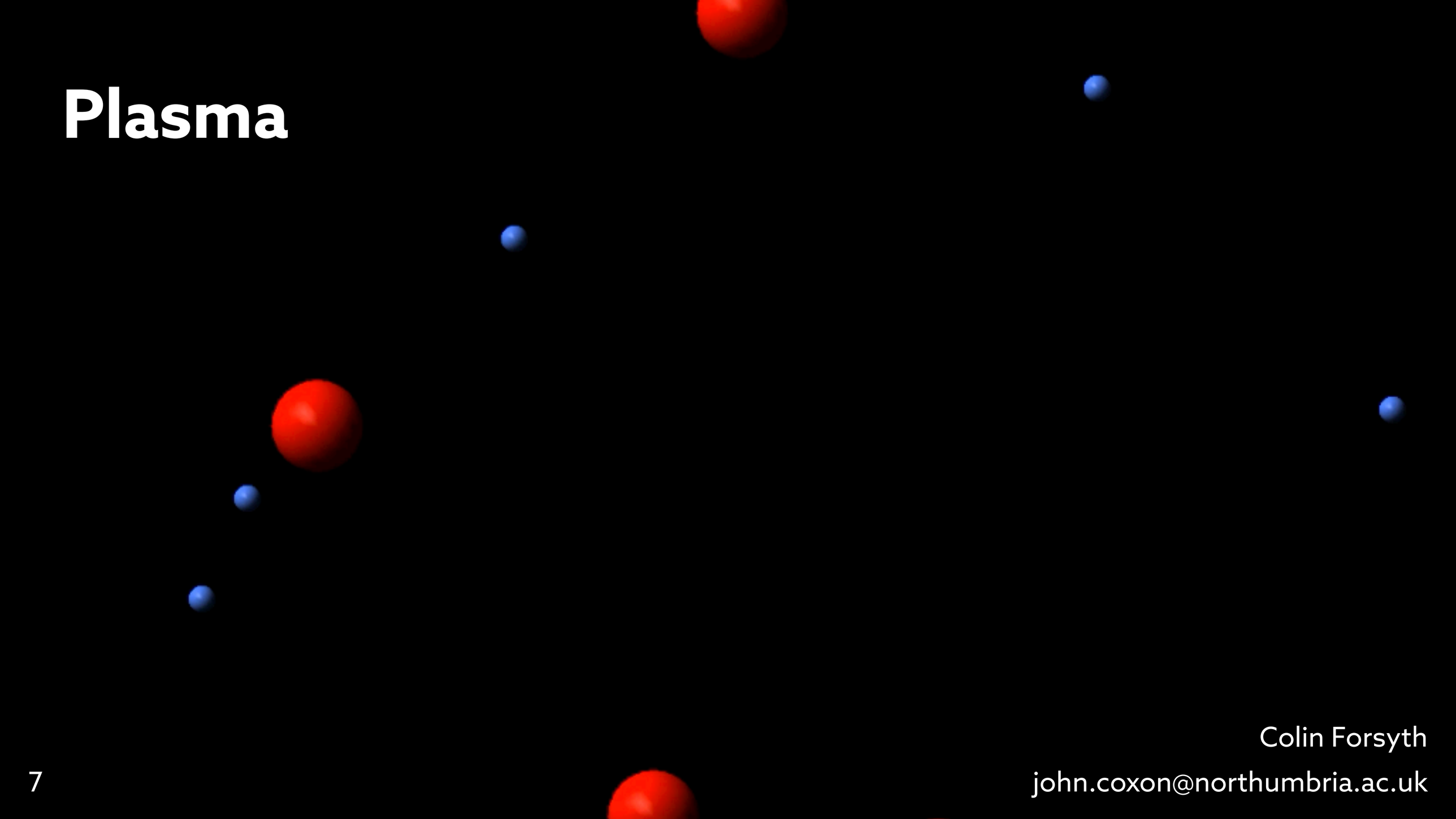
- Gyration
  - Particles gyrate around field lines as they move along them
- Bounce
  - Particles decelerate as magnetic field gets stronger
  - Leads to magnetic mirroring: acceleration in the opposite direction
- Drift
    - ExB, gradient, and curvature drifts
    - Electrons and ions move in opposite directions

john.coxon@northumbria.ac.uk

Plasma



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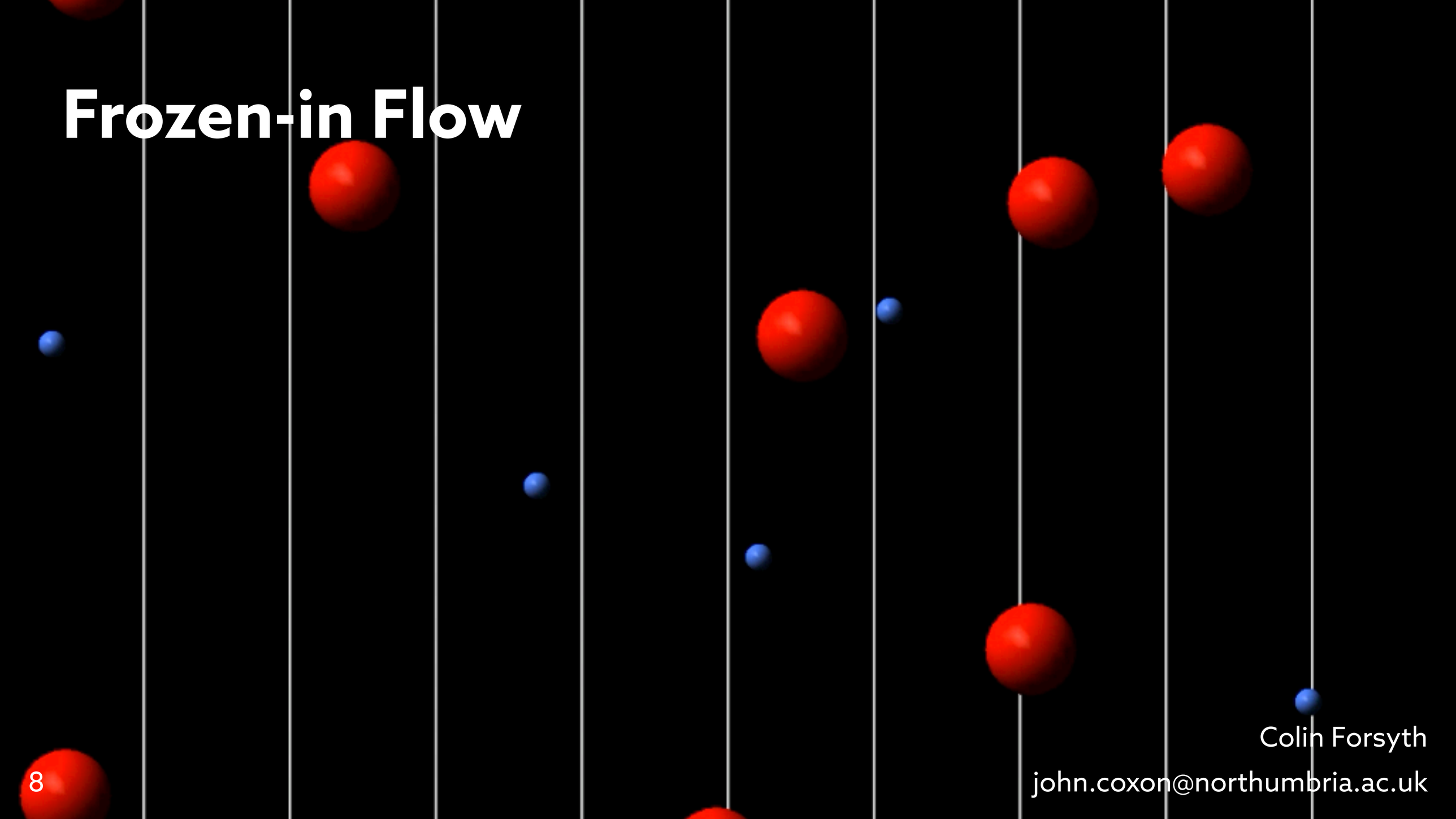
john.coxon@northumbria.ac.uk

Frozen-in Flow



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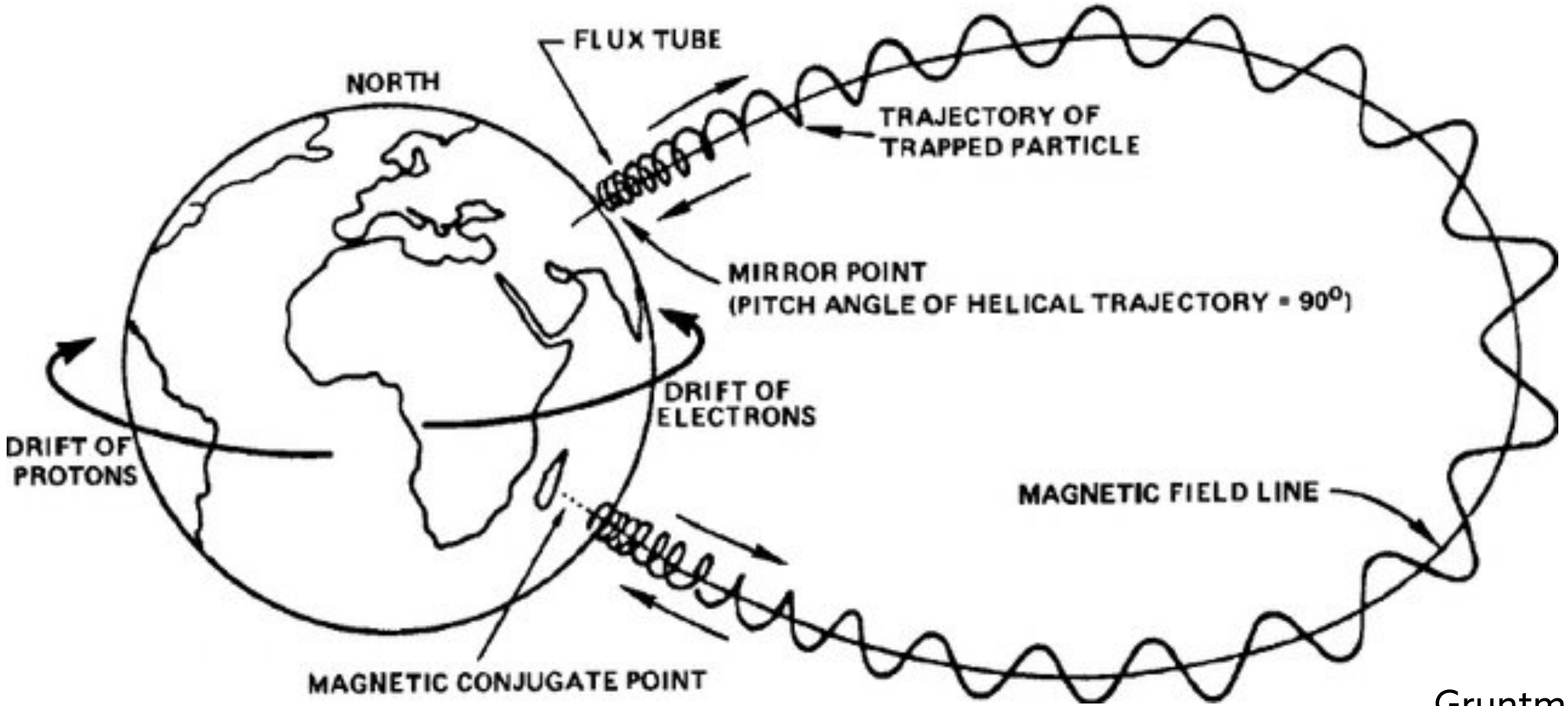
john.coxon@northumbria.ac.uk

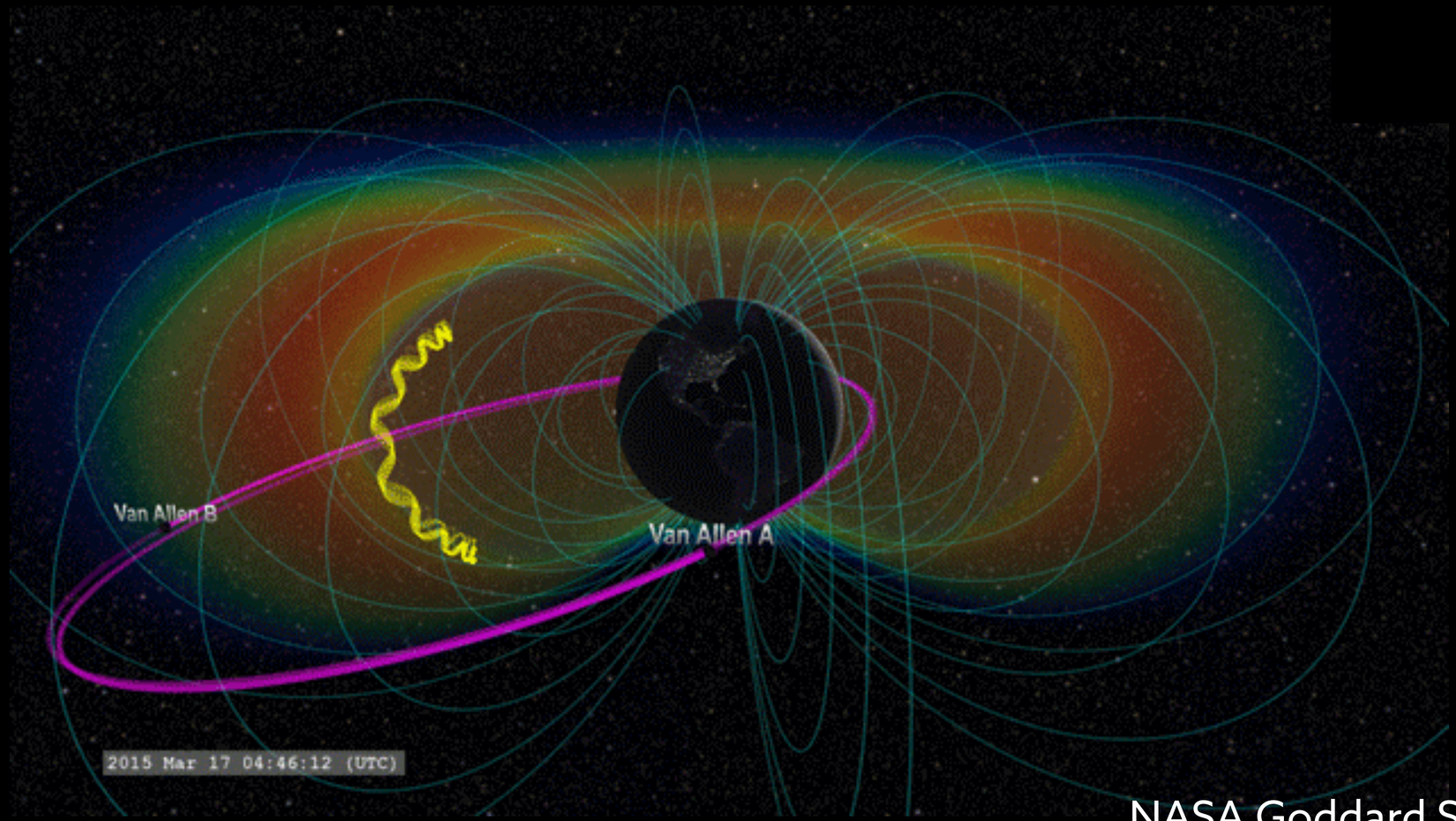
Plasma motion at Earth



Gruntman (1997)

john.coxon@northumbria.ac.uk

Plasma motion at Earth



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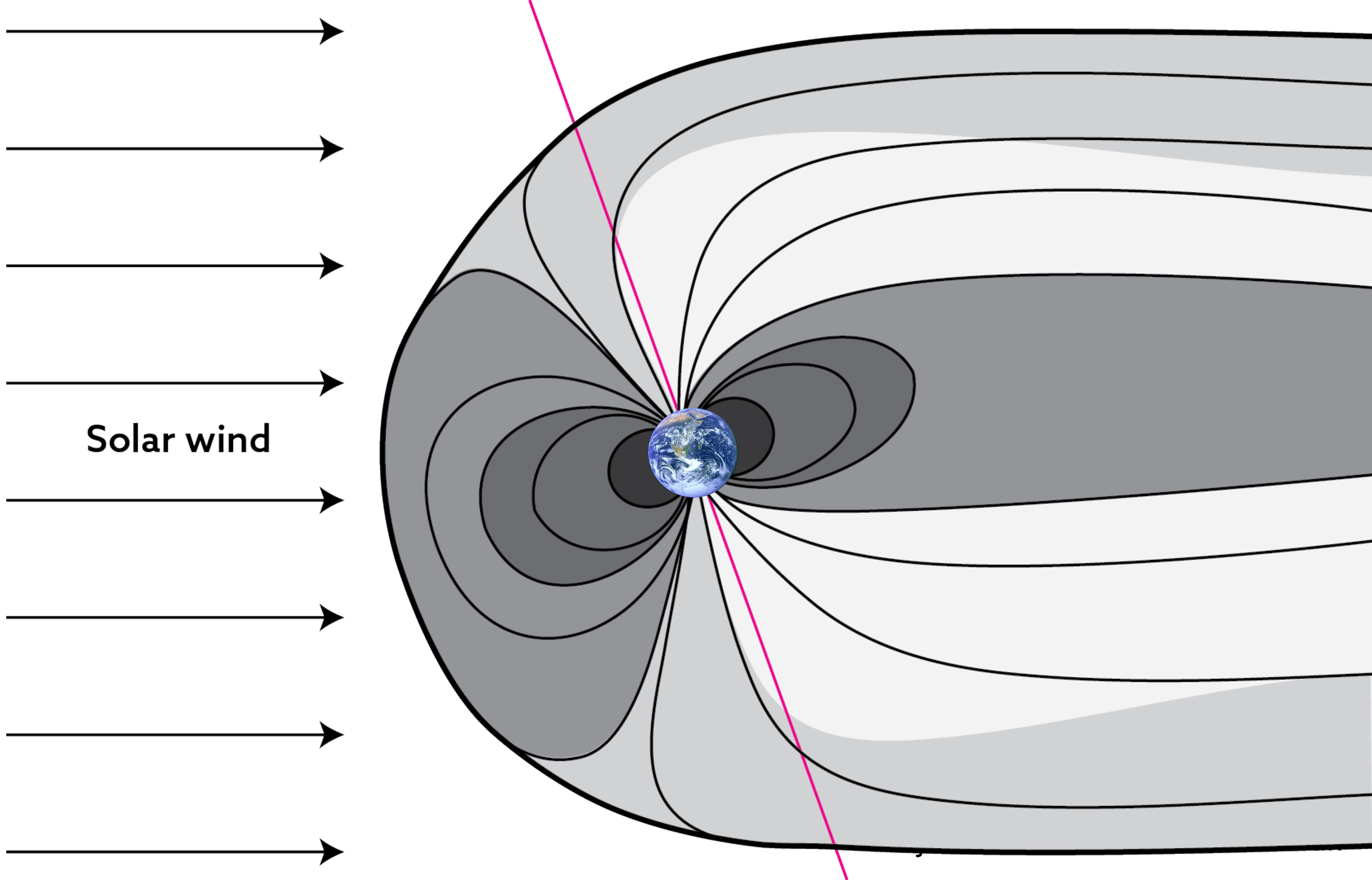
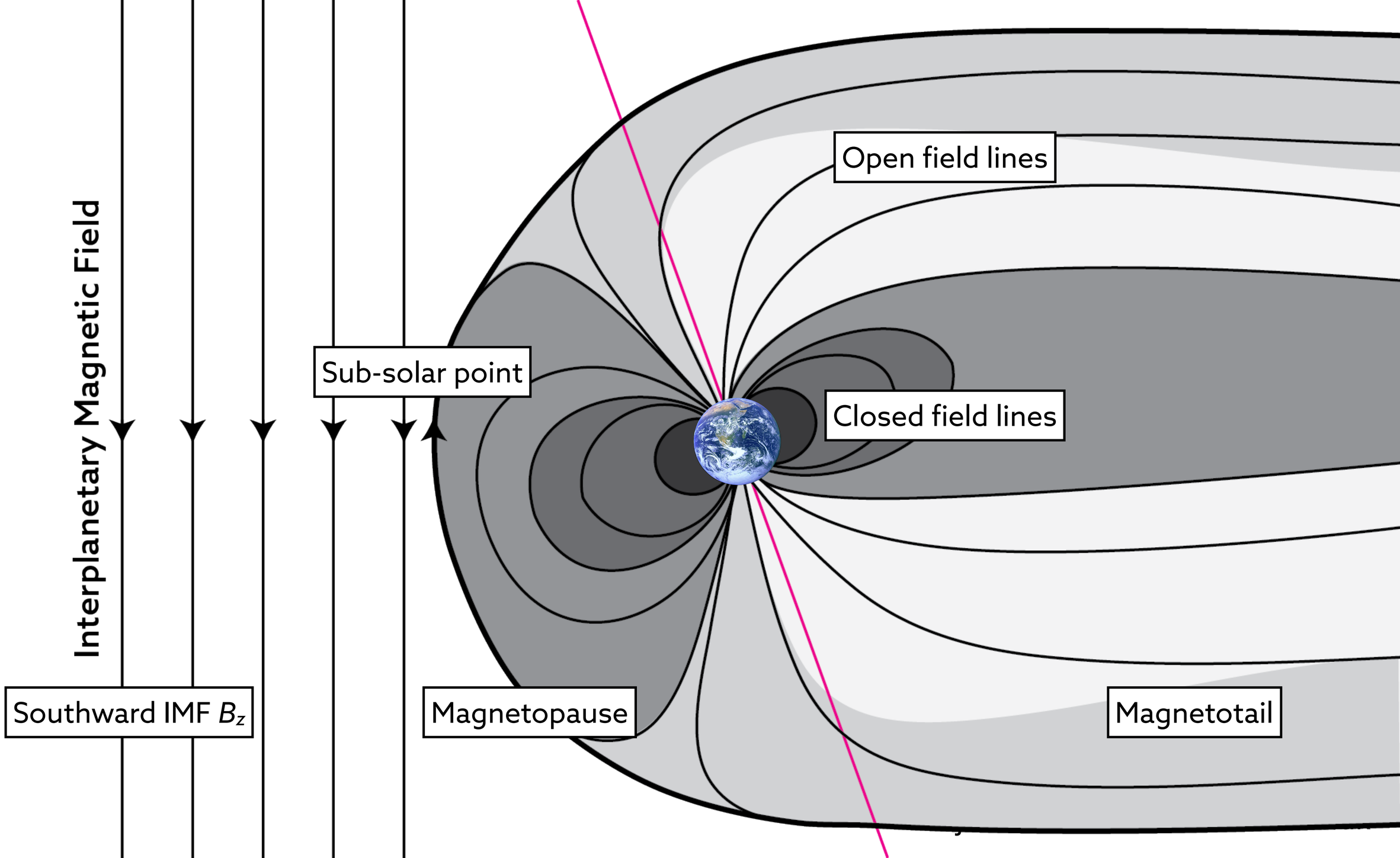

Solar wind


Interplanetary Magnetic Field
Sub-solar point
Open field lines
Closed field lines
Southward IMF B_z
Magnetopause
Magnetotail

Why do we see magnetospheres?

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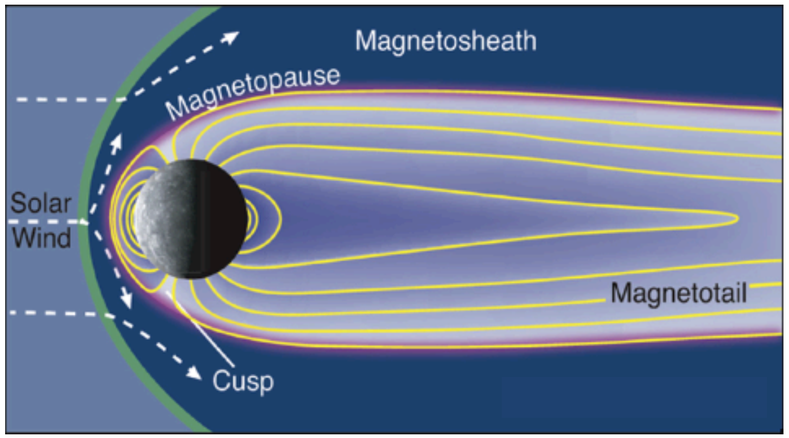
Plasmas cannot mix because of frozen-in-flow approximation

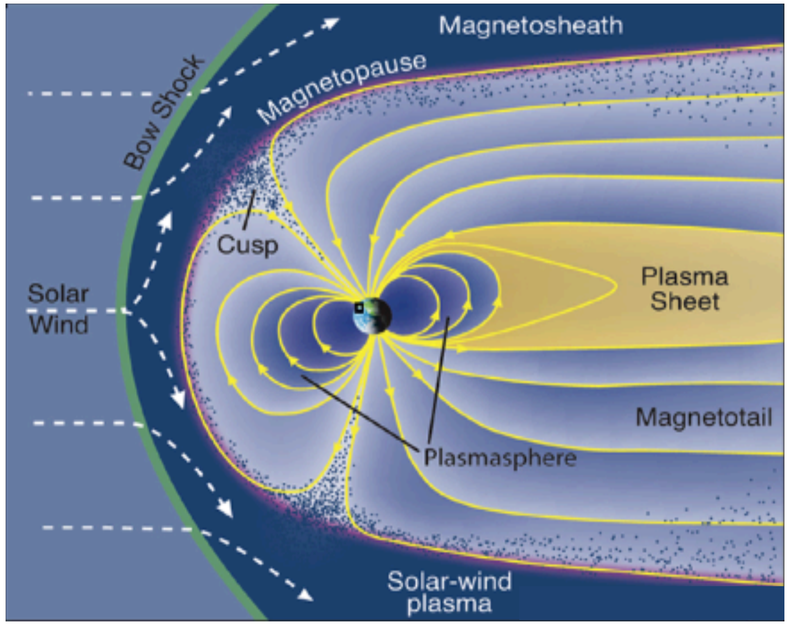
Therefore, cavities in the solar wind must form around magnetic fields dictated by pressure balance

john.coxon@northumbria.ac.uk

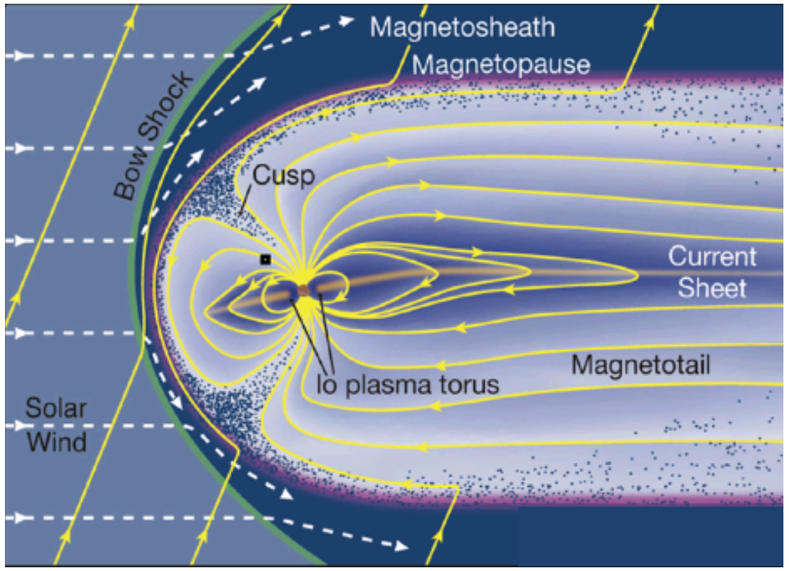
Different pressure balances



Mercury (~400x)



Earth (~40x)



Jupiter (~1x)

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john.coxon@northumbria.ac.uk

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The Dungey Cycle

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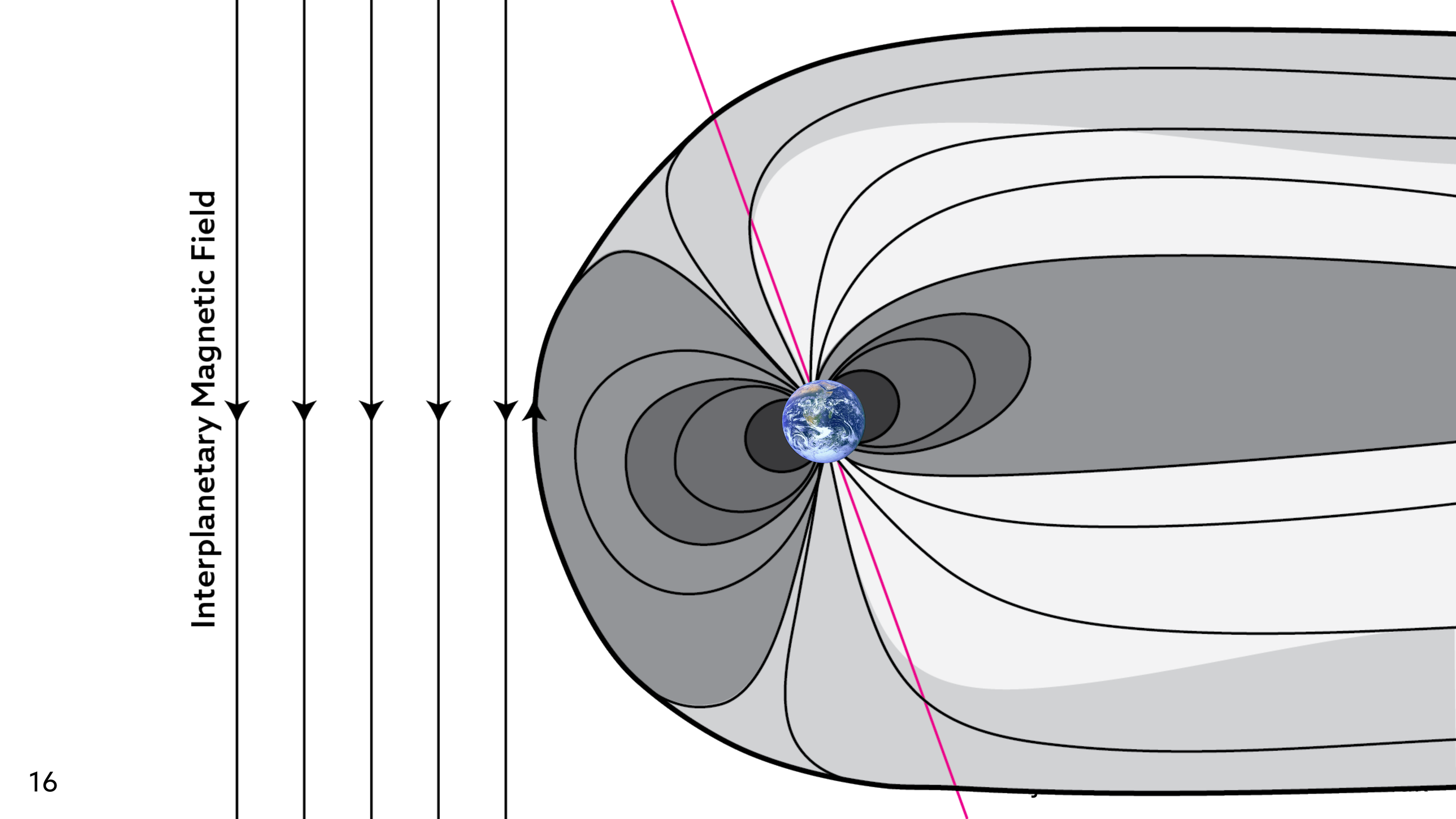
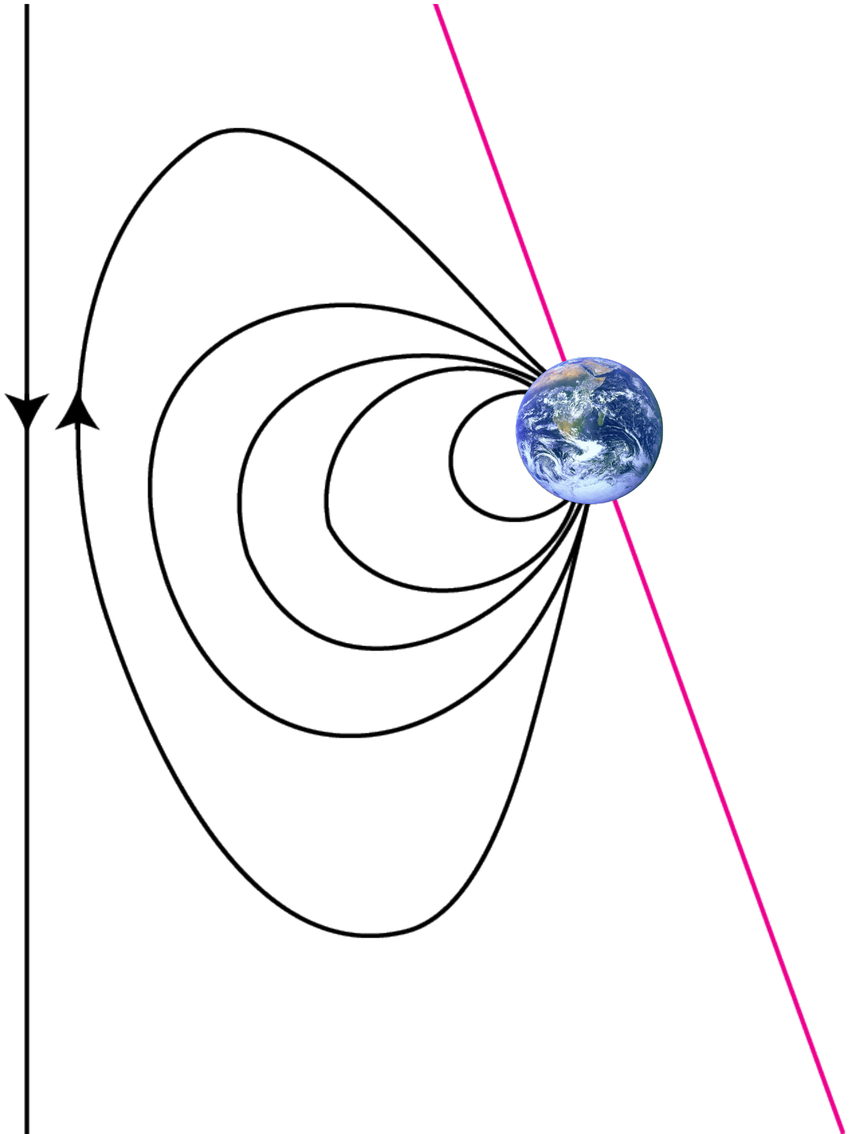

Interplanetary Magnetic Field

Closed field line and southward B_z



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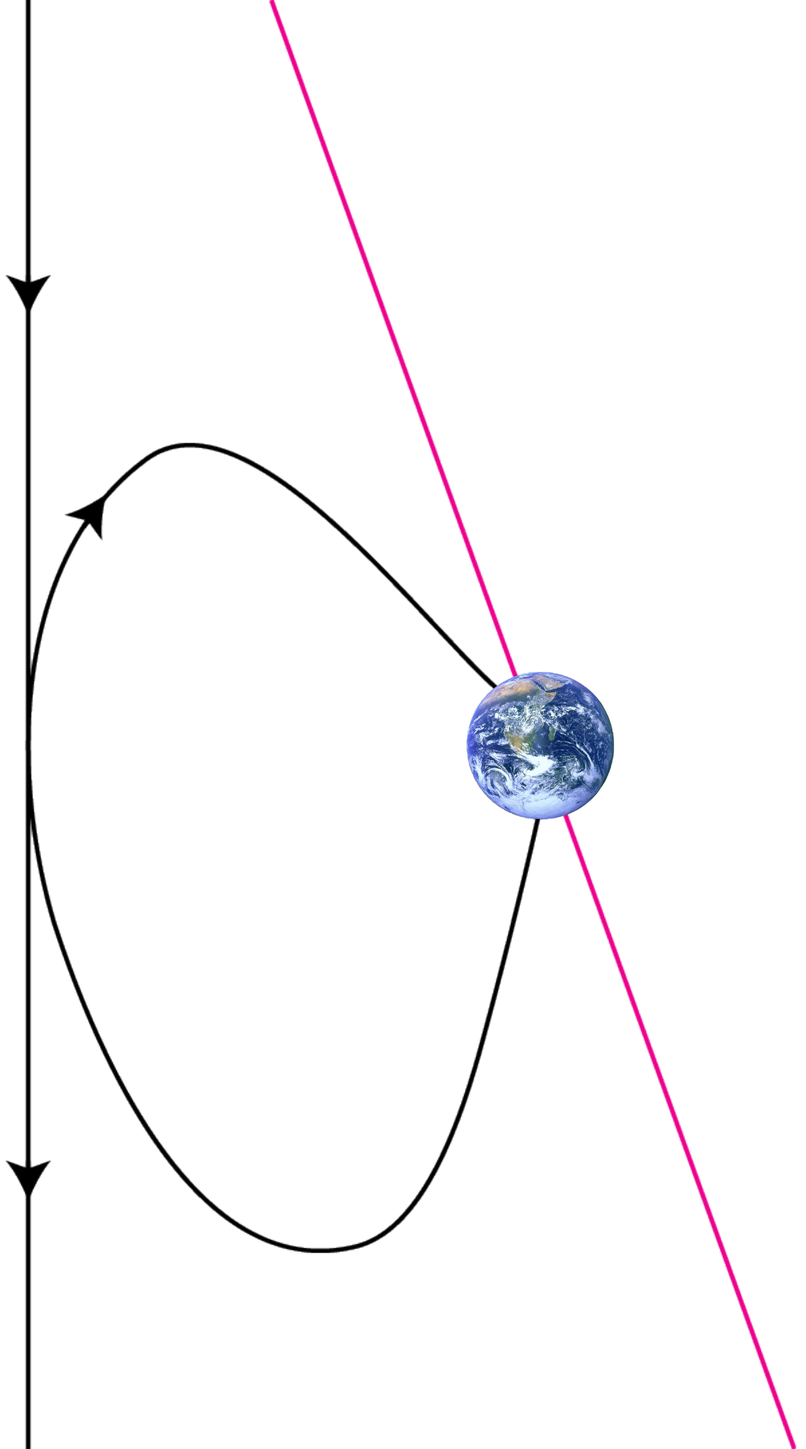
Reconnection



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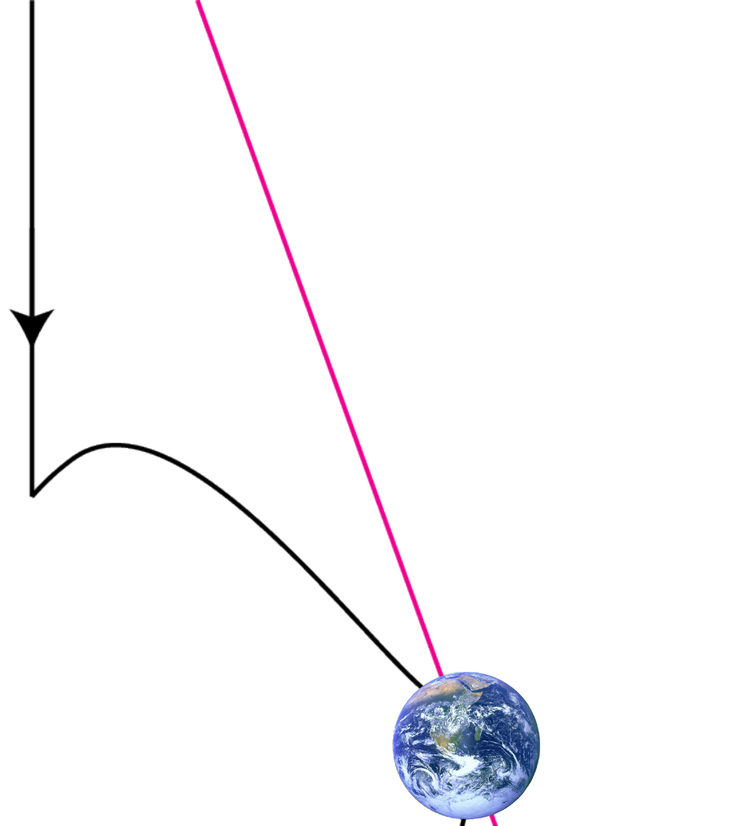
Open field line



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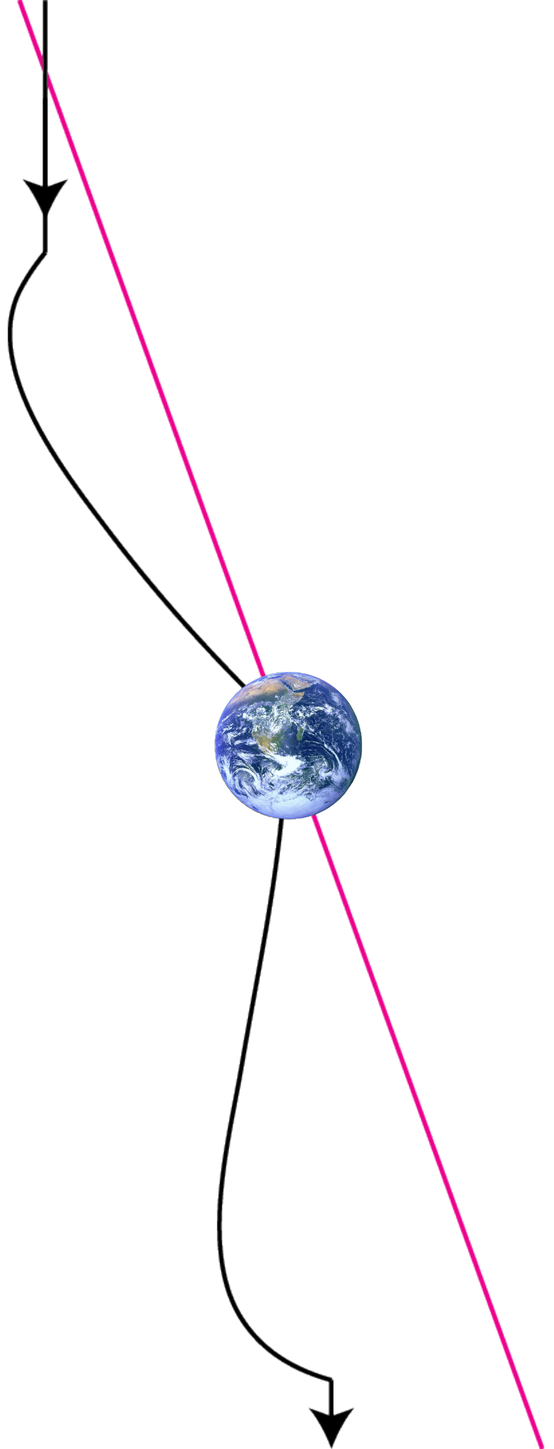
Open field line



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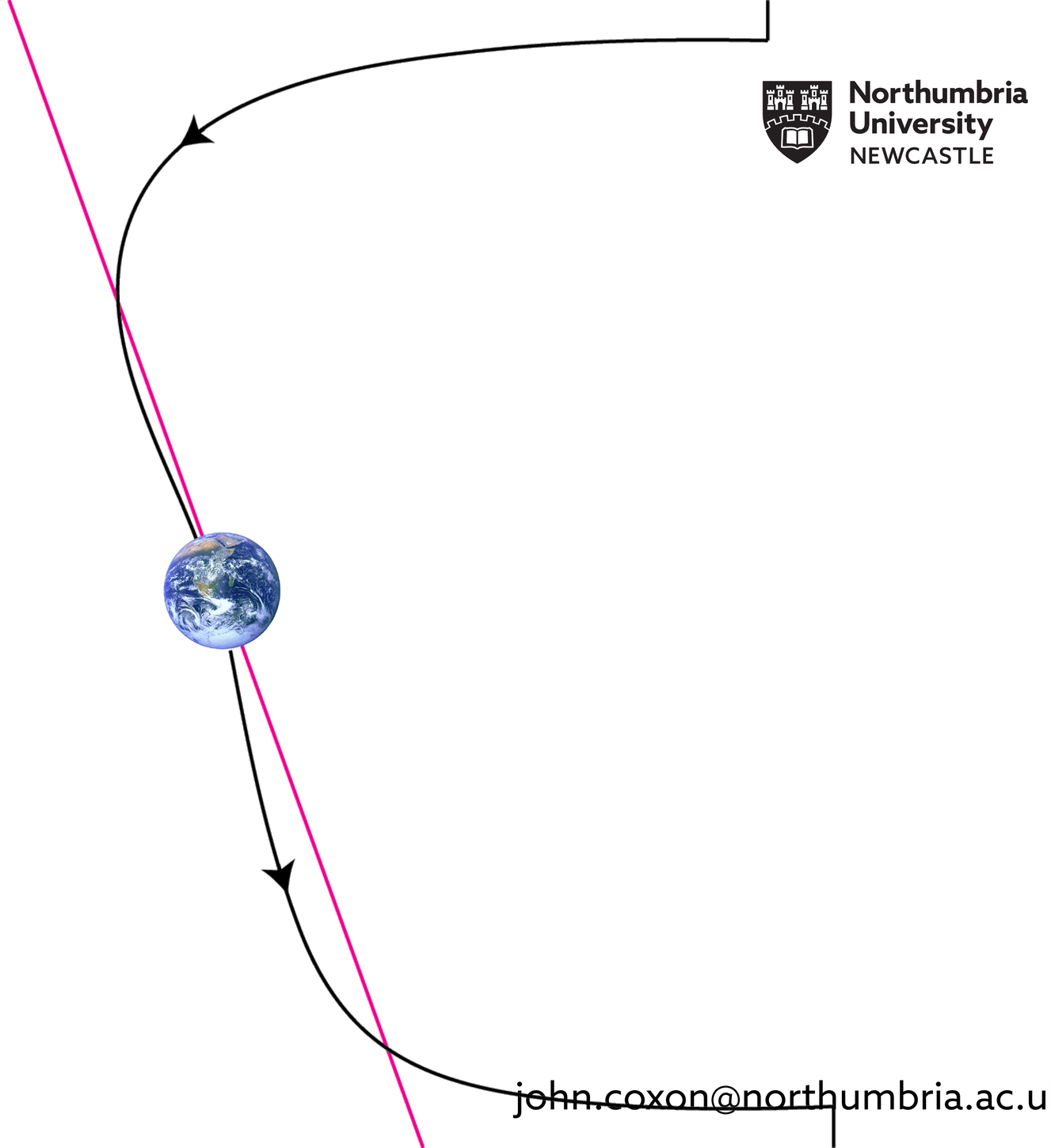
Open field line



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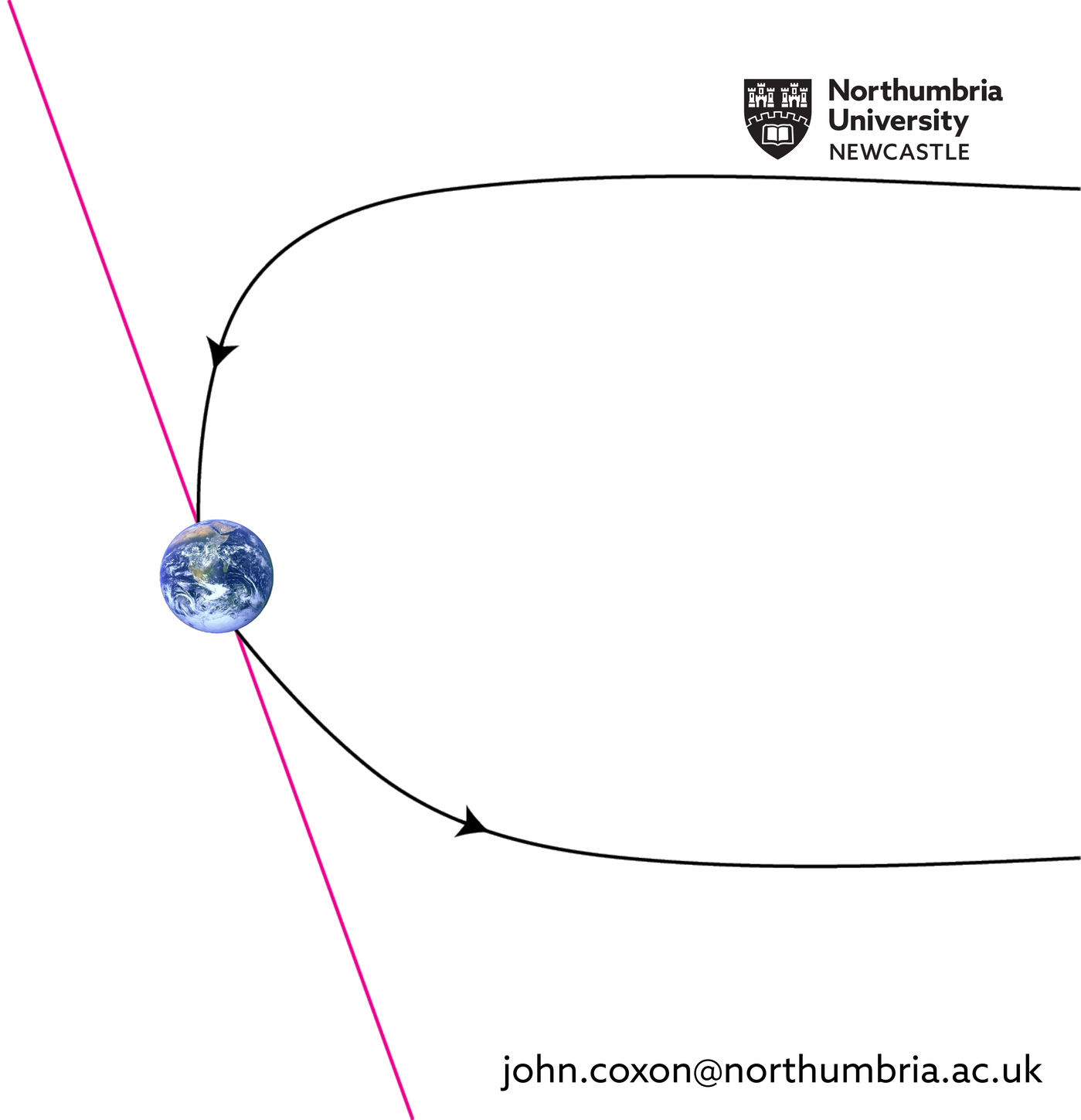
Open field line



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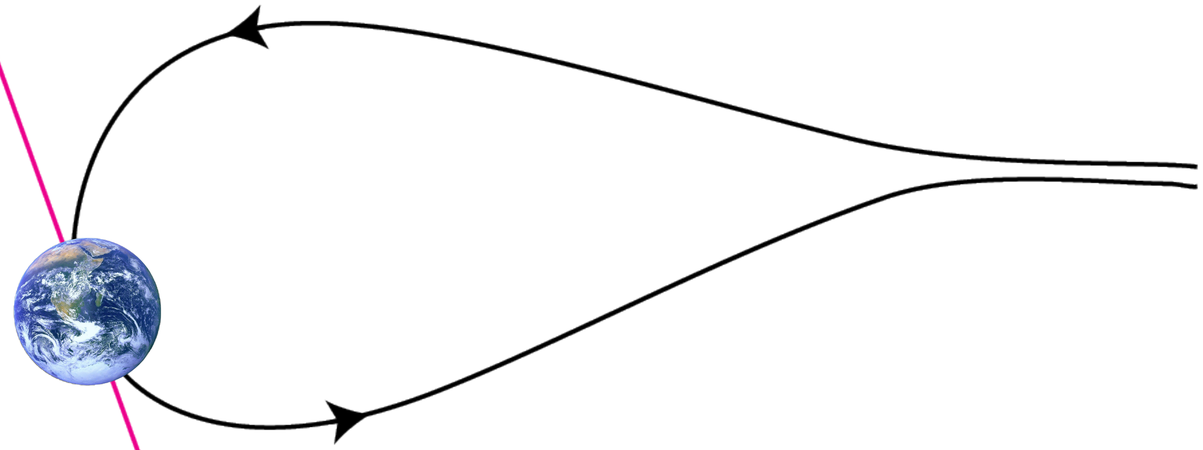
Open field line



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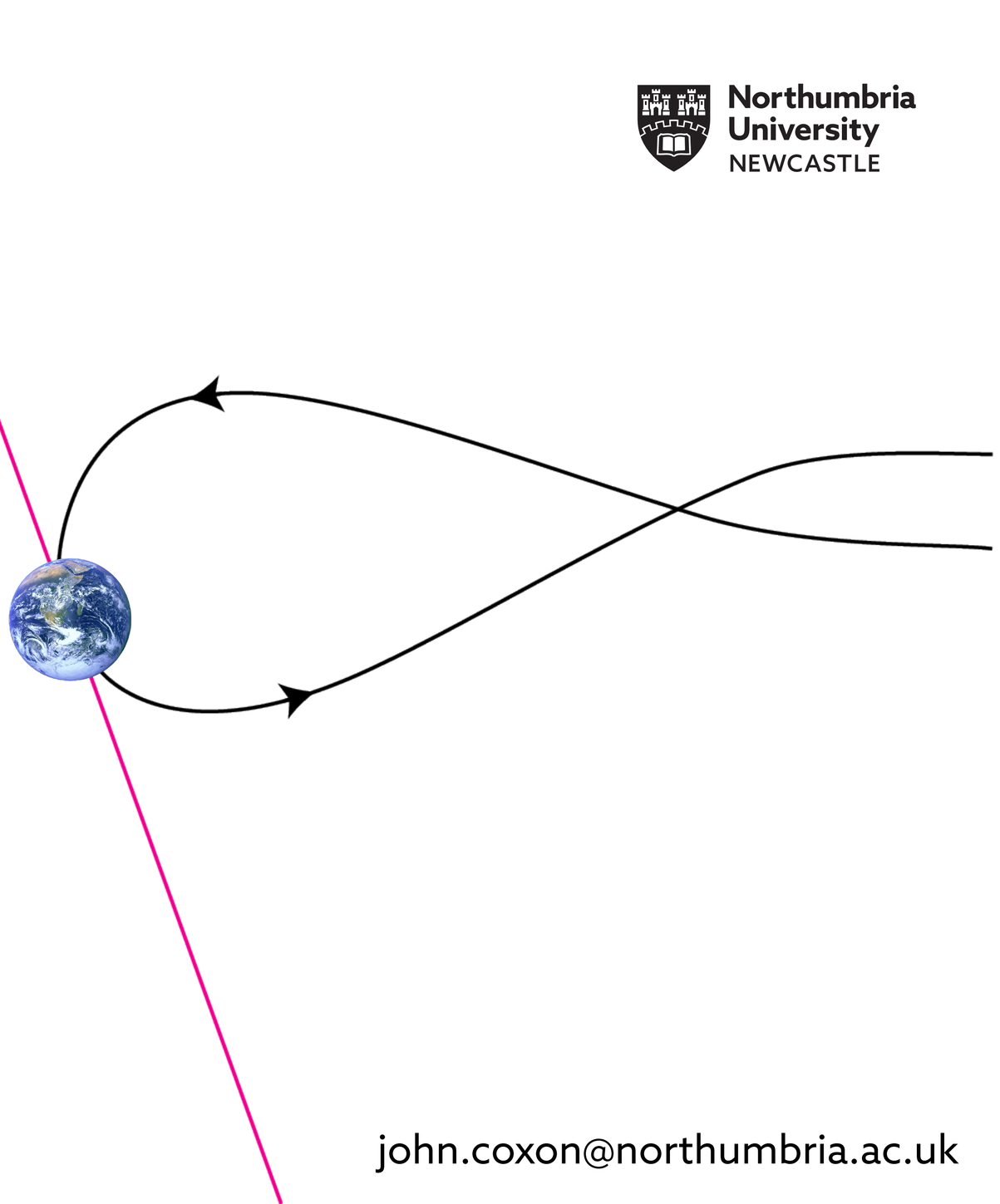
Reconnection



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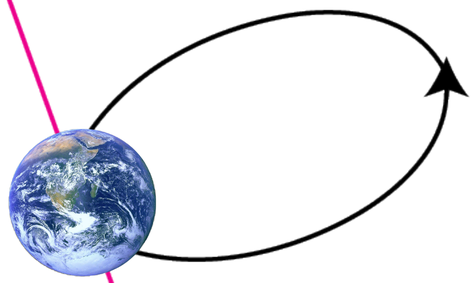
Closed field line



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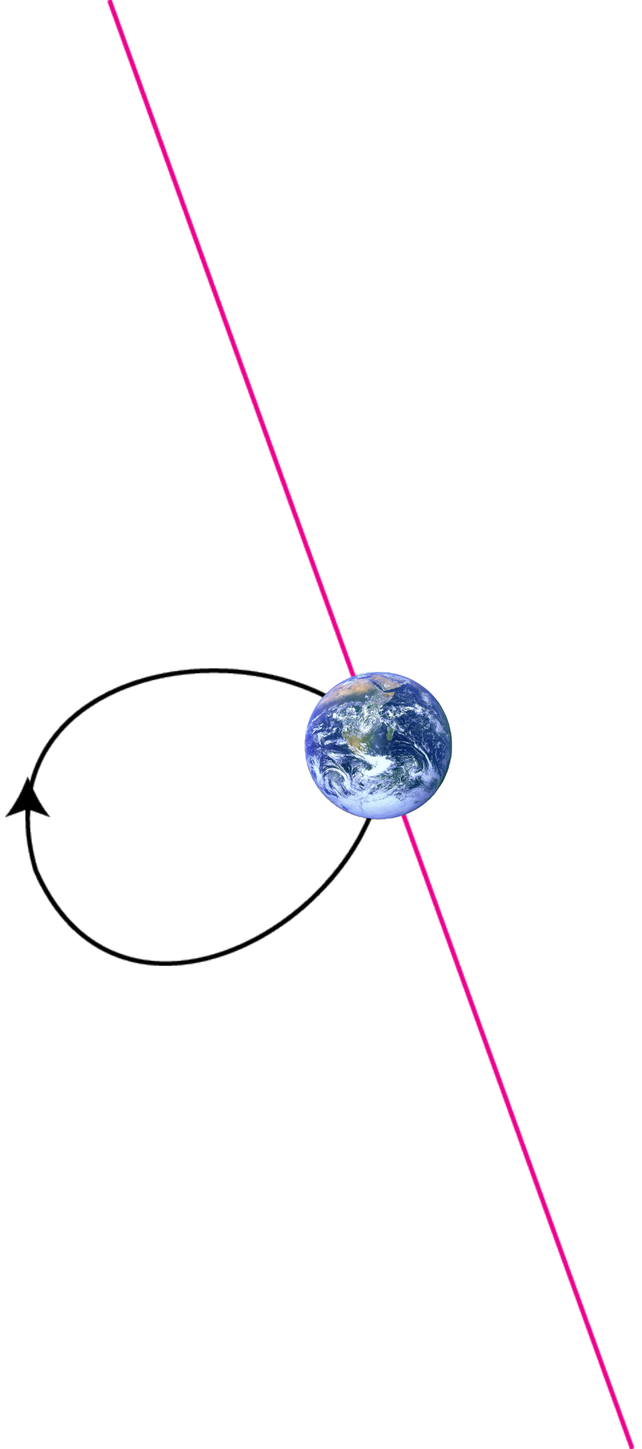
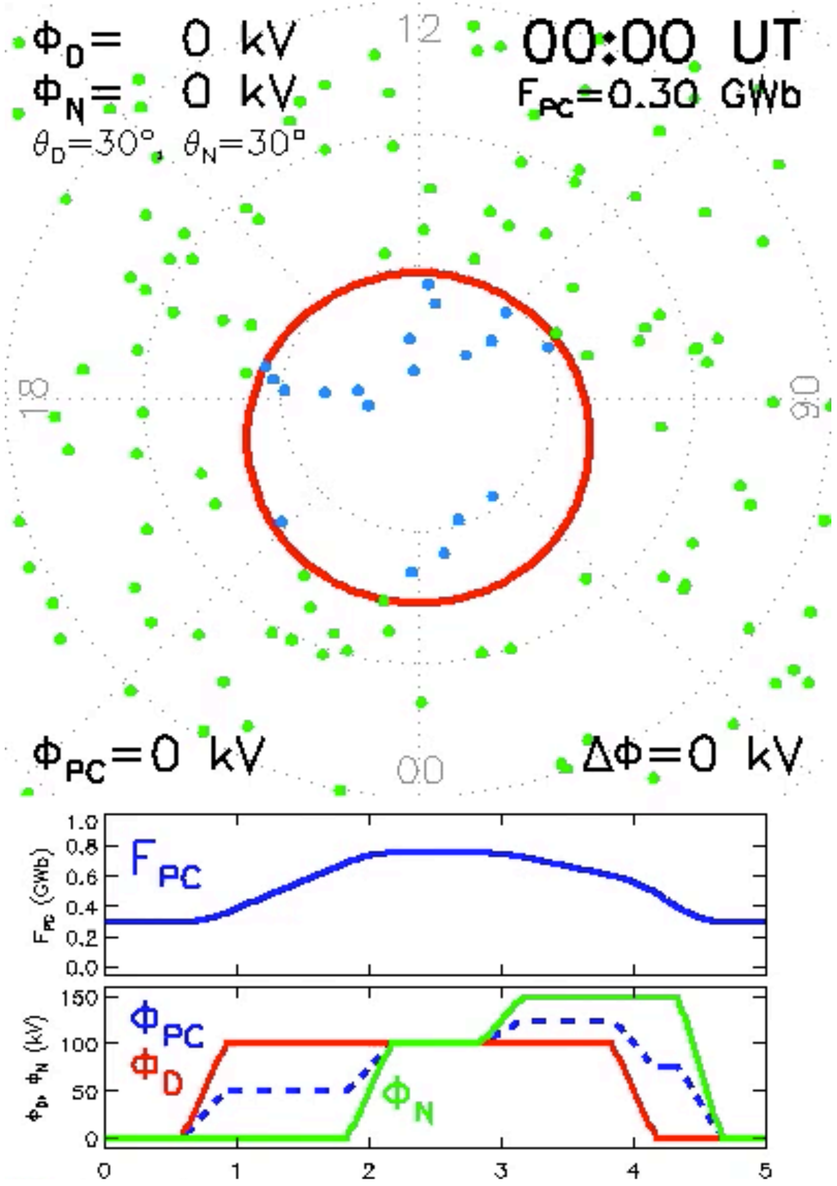
Closed field line



john.coxon@northumbria.ac.uk

From above the polar cap

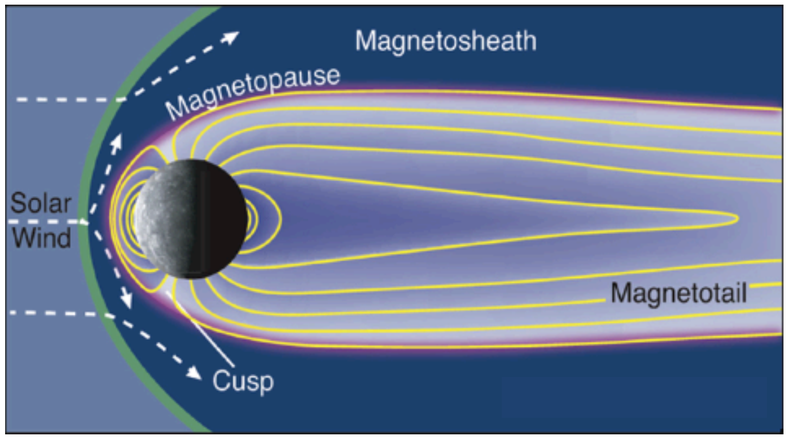
- The polar cap moves equatorward and poleward (Siscoe & Huang, 1985)
- Expanding/contracting polar cap (ECPC) paradigm (Cowley & Lockwood, 1992)
  - Antisunward flow across the polar cap
  - Sunward flow around the flanks of the polar cap



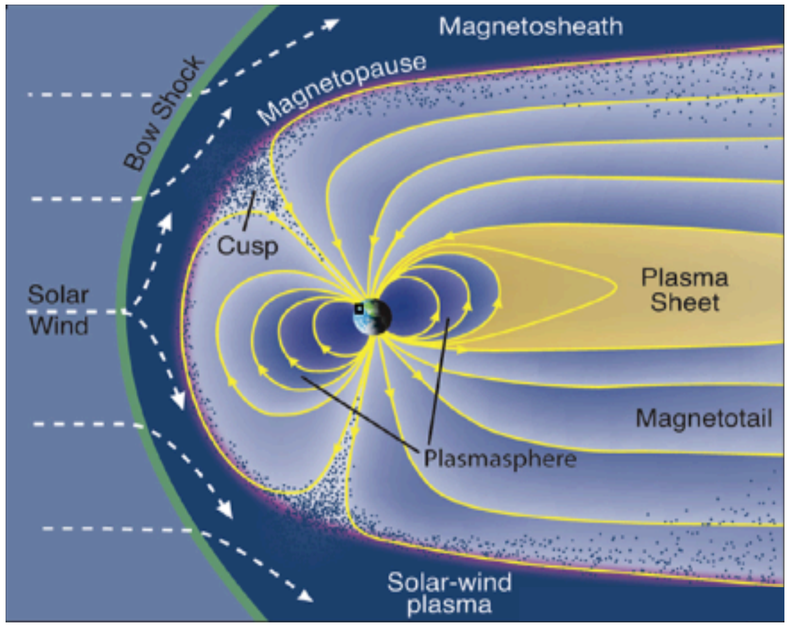
Steve Milan

john.coxon@northumbria.ac.uk

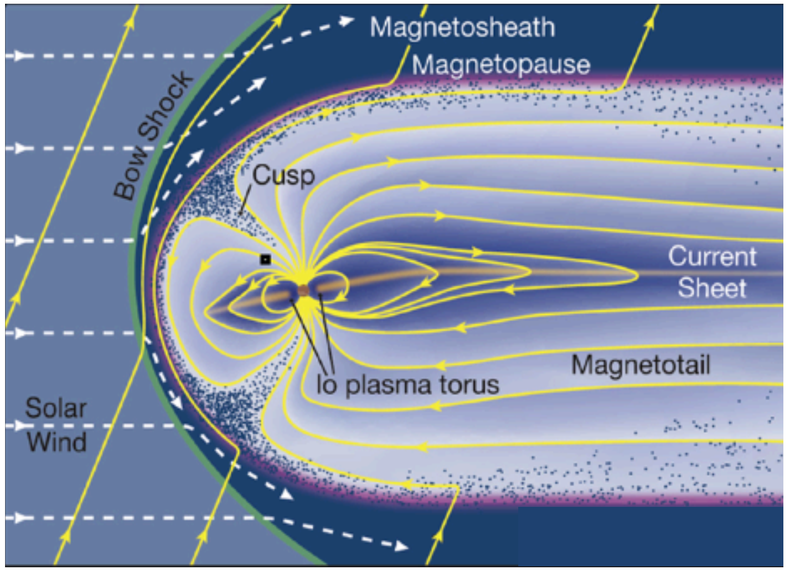
Different magnetic interactions



Mercury (~400x)



Earth (~40x)

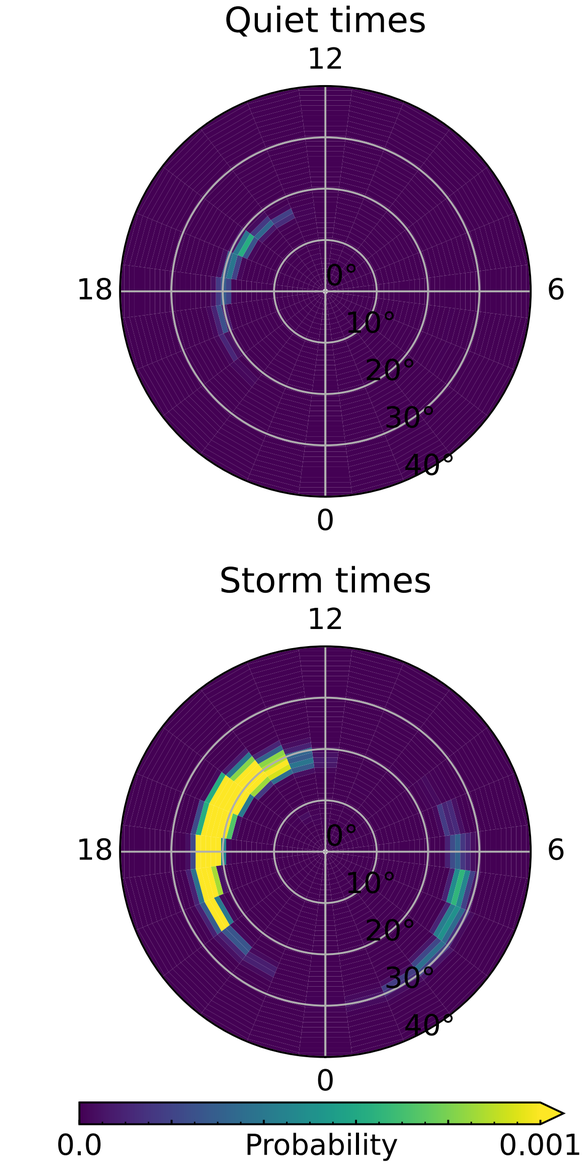


Jupiter (~1x)

Fran Bagenal & Steve Bartlett
john.coxon@northumbria.ac.uk

Geomagnetic storms

- Geomagnetic storms are periods of enhanced solar wind driving of the magnetosphere
- They are characterised by innately higher variability than quiet times or substorm times
- Therefore they drive more extreme behaviour
- Forecasting these storms is a huge area of research at the moment because of this
- This should really be a whole talk!

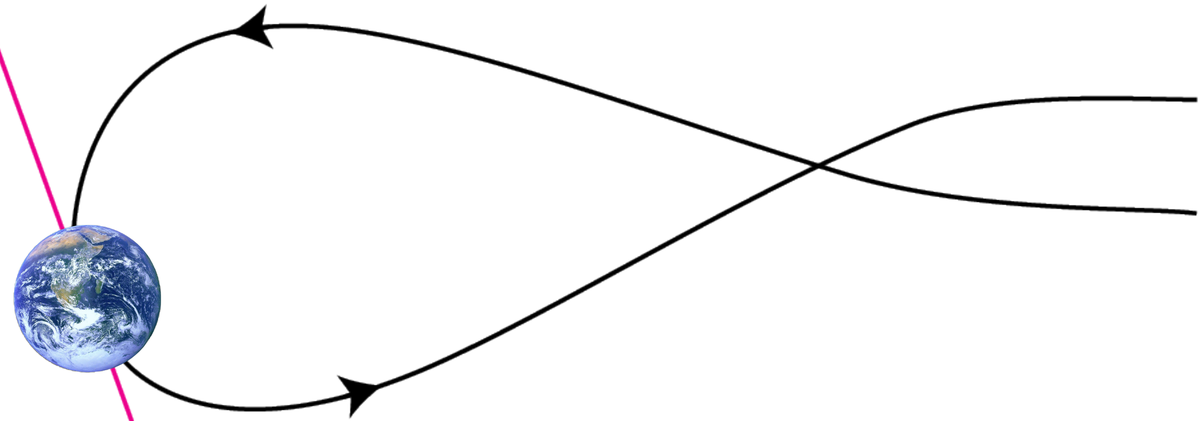


Coxon et al. (2022)

john.coxon@northumbria.ac.uk

Substorms

- Nightside reconnection occurs in the Dungey Cycle
- Substorms are the name given to the bursty magnetic reconnection events in the magnetotail
- They energise particles on the nightside of the Earth



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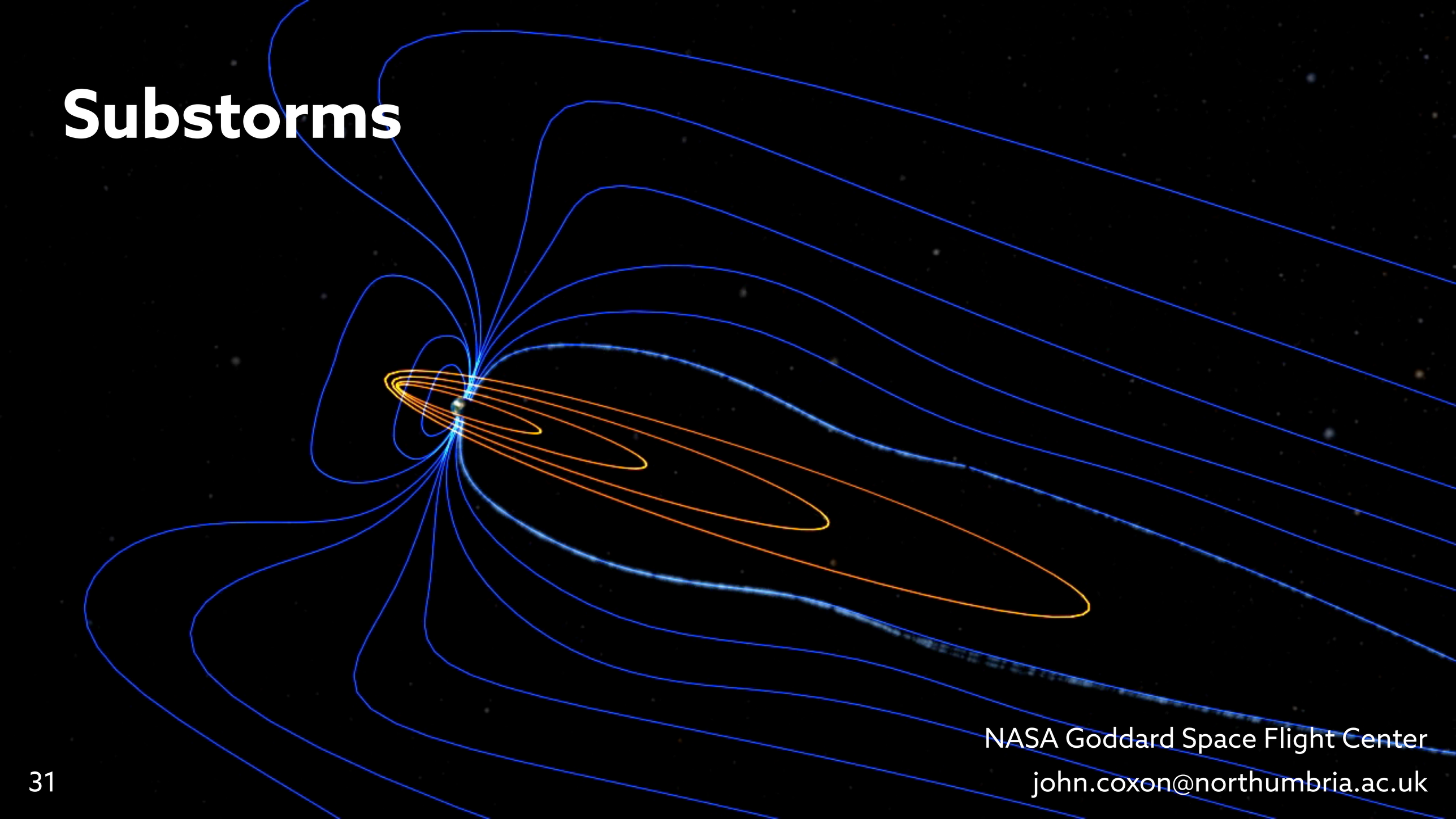
Substorms



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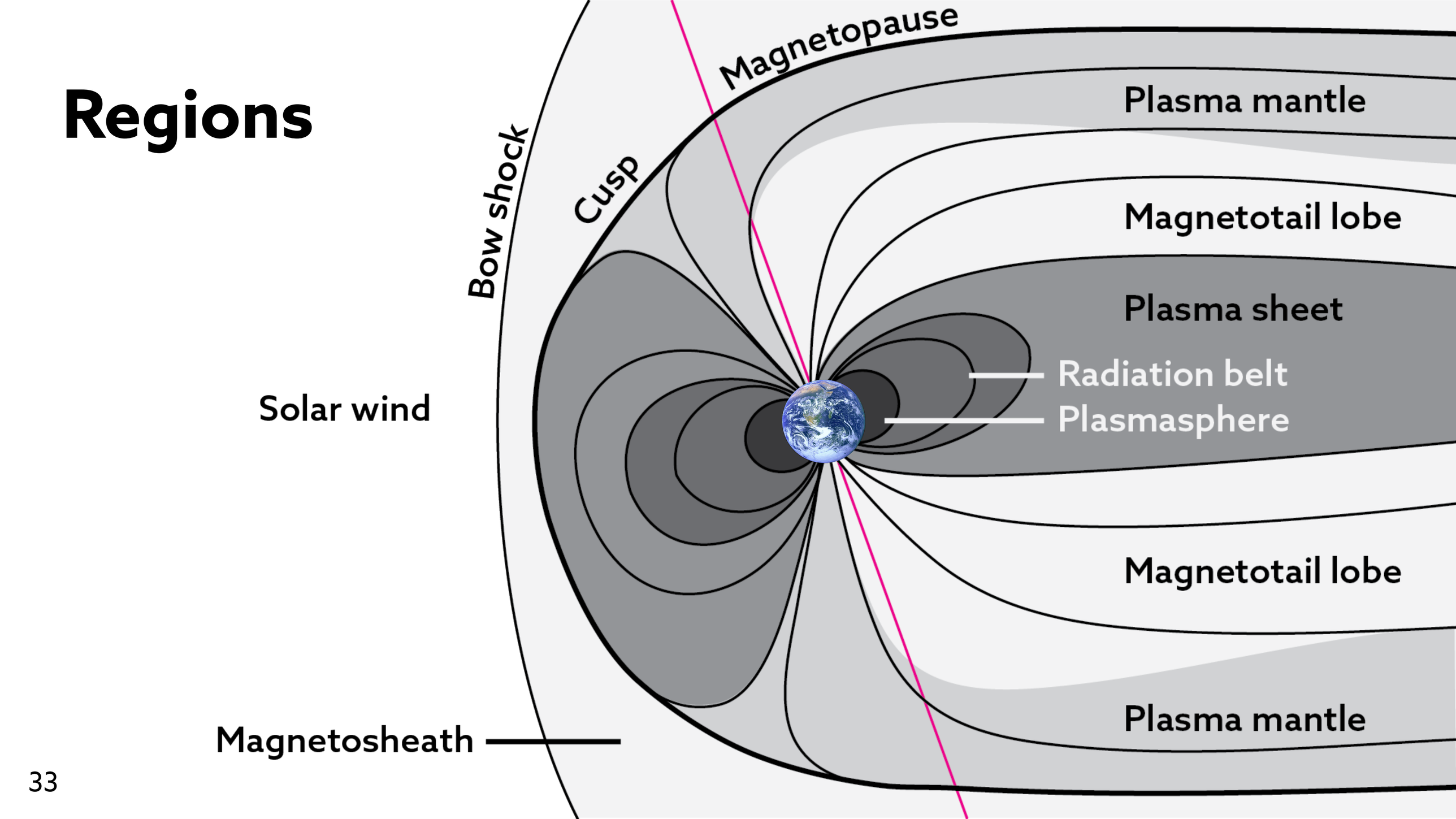
Particle populations in the magnetosphere

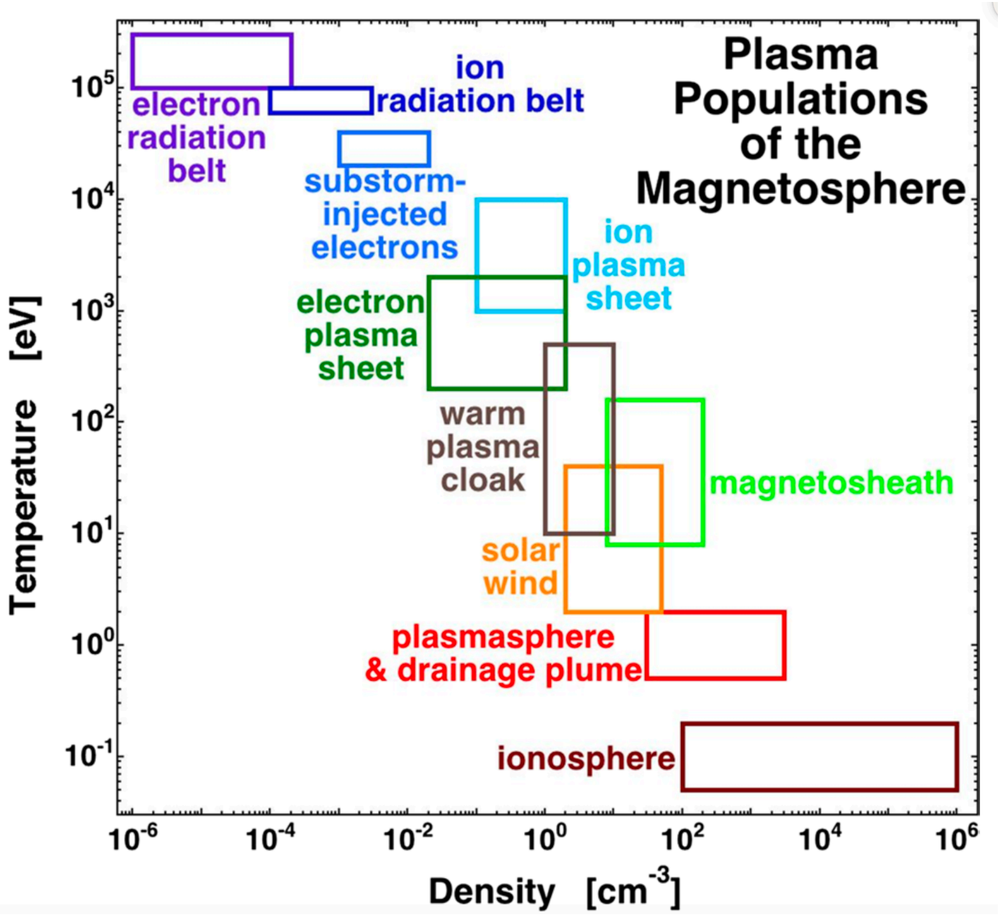
john.coxon@northumbria.ac.uk

Regions


Solar wind
Bow shock
Magnetopause
Cusp
Plasma mantle
Magnetotail lobe
Plasma sheet
Radiation belt
Plasmasphere
Magnetotail lobe
Plasma mantle
Magnetosheath

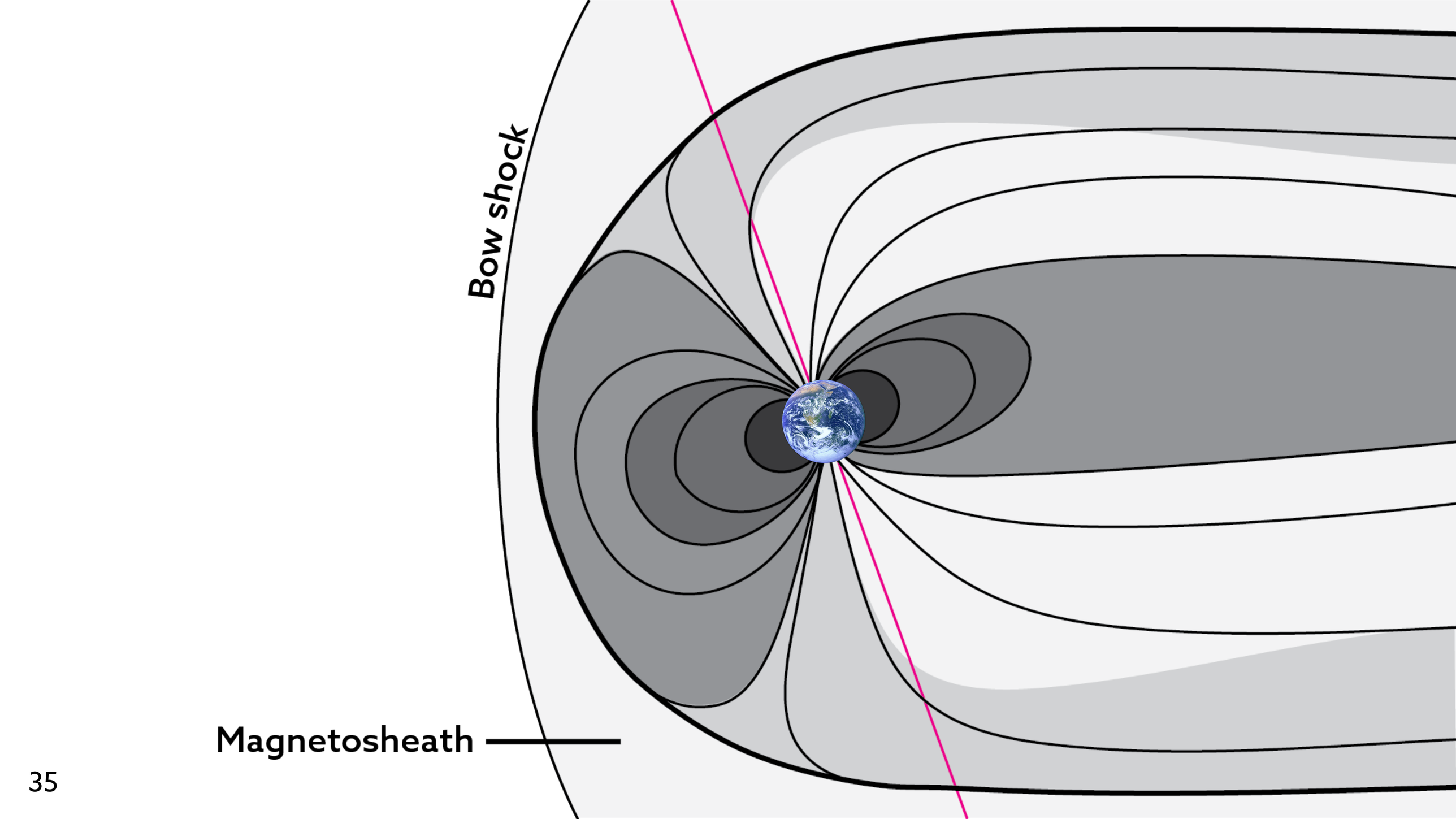
Temperature and density

- There are many different plasma populations in the magnetosphere
- Note the log scales!
  - 7 orders of magnitude in temperature
  - 12 orders of magnitude in density
- I'll cover most of these regions in the next few slides and then come back to this image



Borovsky & Valdivia (2018)

john.coxon@northumbria.ac.uk

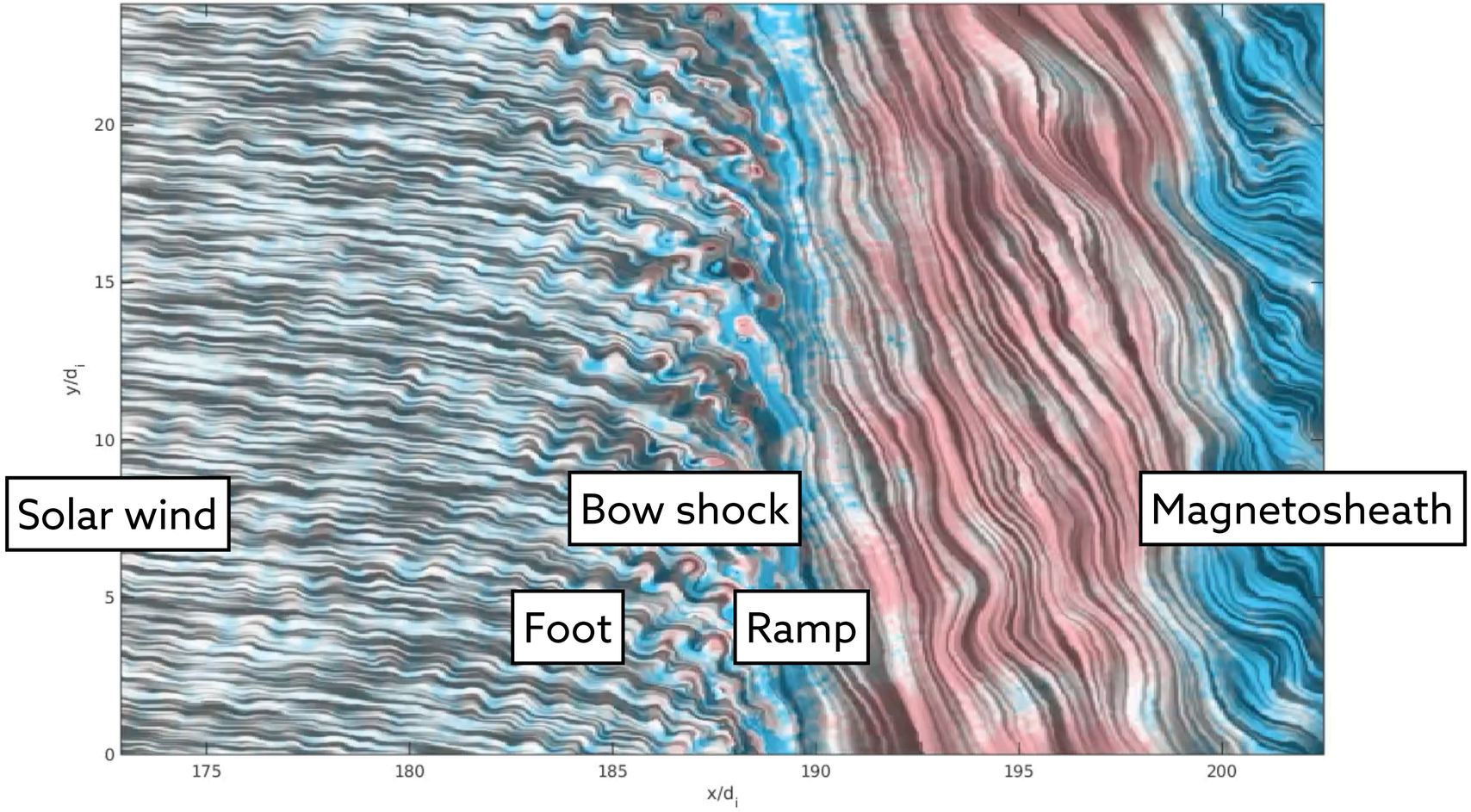

Bow shock
Magnetosheath

Bow shock and magnetosheath

- Solar wind plasma is supersonic (above the Alfvén speed)
- It hits the cavity formed by the magnetosphere
- This causes the bow shock as the plasma becomes subsonic
- The region of shocked plasma between the bow shock and magnetopause is called the magnetosheath
- Filled with turbulent plasma and magnetic fields
- To be honest, I refer to this as “the complicated bit”

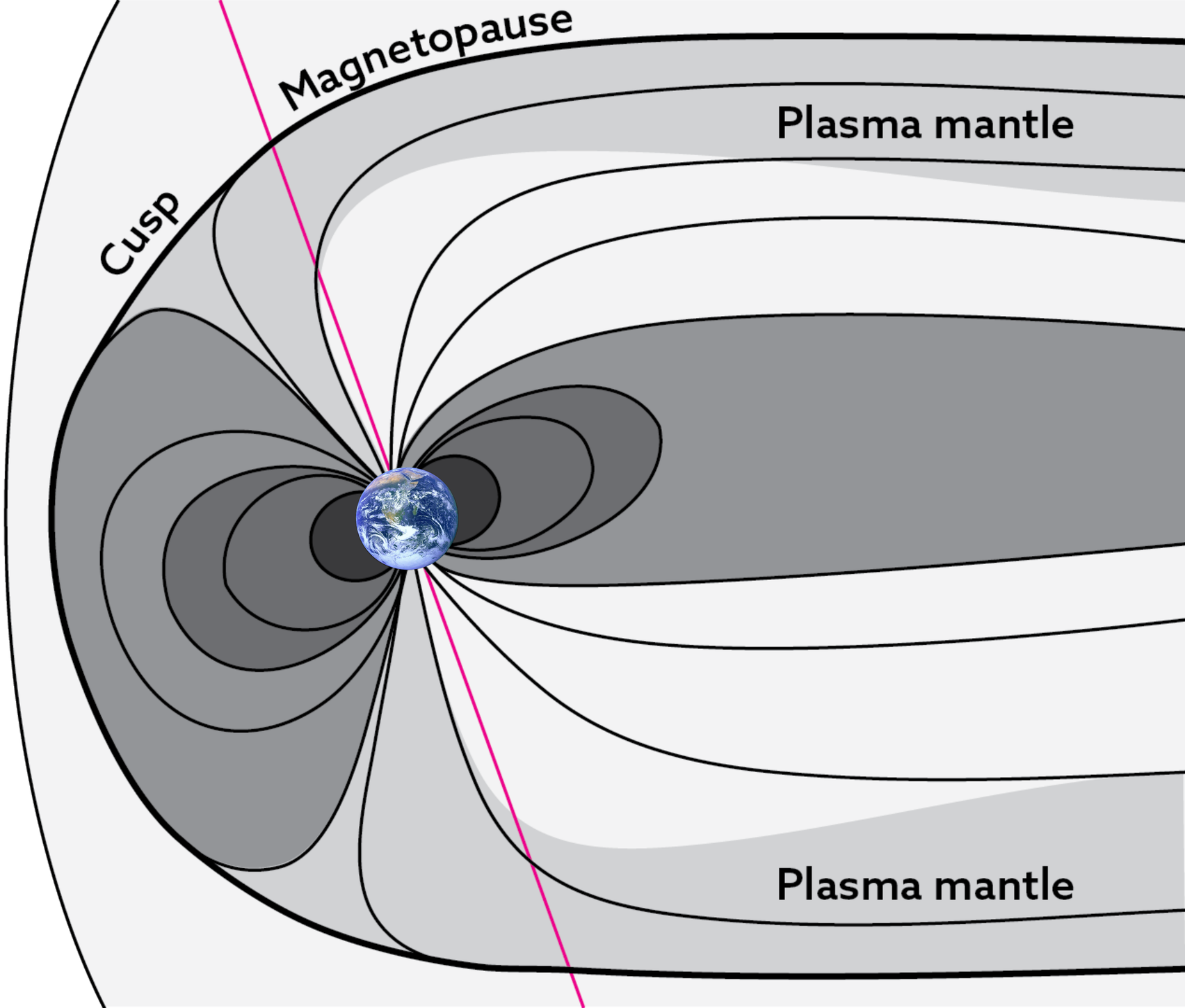
john.coxon@northumbria.ac.uk

Bow shock and magnetosheath



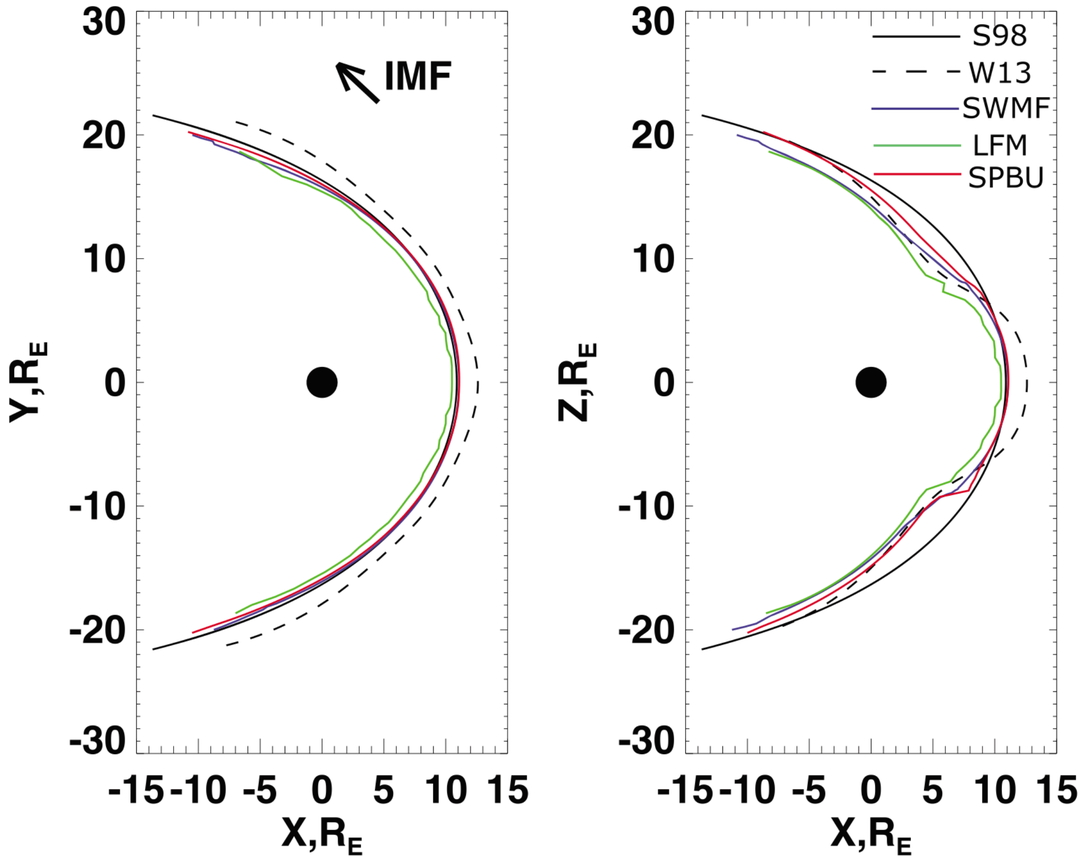
Gingell et al. (2017)

john.coxon@northumbria.ac.uk


Magnetopause
Plasma mantle
Cusp
Plasma mantle

Magnetopause

- The boundary between the Earth's and Sun's magnetic fields
- Its position is (probably) reliant on
  - Pressure
  - IMF B_z
  - Dipole tilt angle
- Models are of varying qualities: be aware of pros and cons before use!



Samsonov et al. (2016)

john.coxon@northumbria.ac.uk

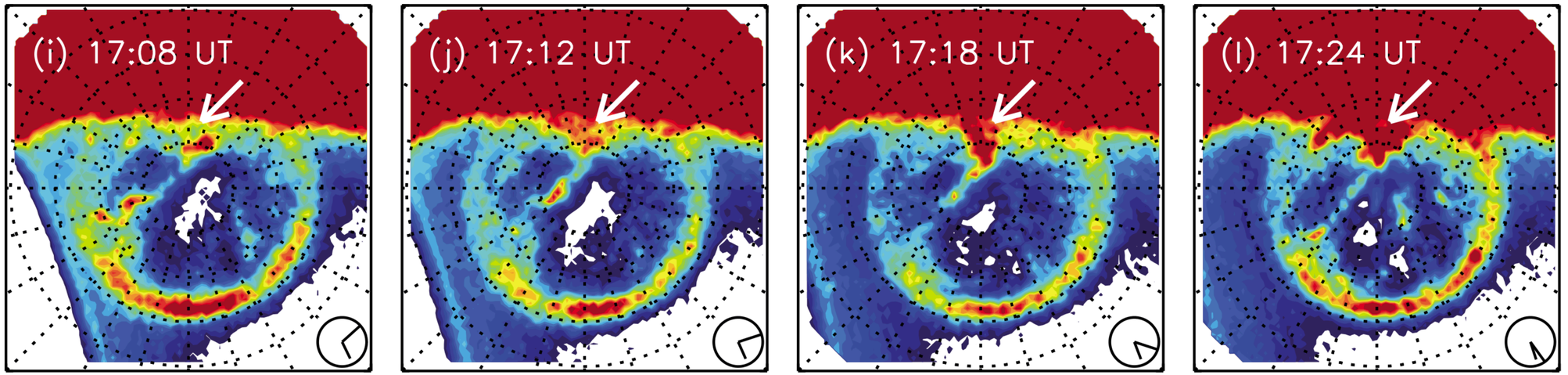
Magnetopause boundary layers

- The cusp
  - Also known as the entry layer
- The plasma mantle
  - Also known as the high-latitude boundary layer (HLBL)
- The low-latitude boundary layer (LLBL)
  - Why doesn't it get a cool pseudonym?
  - This is an open question in the field

john.coxon@northumbria.ac.uk

Cusp (aka the entry layer)

- Arises due to newly opened magnetic field lines
- Comprises sheath plasma entering the magnetosphere directly
- Leads to the cusp spot in the auroras (white arrows below)



Fear et al. (2015)

john.coxon@northumbria.ac.uk

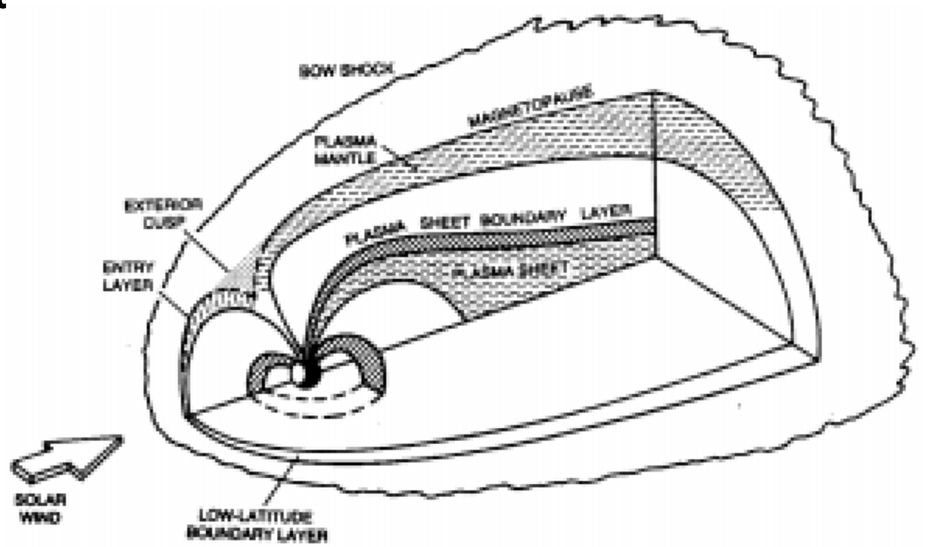
Plasma mantle

- Also known as the high-latitude boundary layer (HLBL)
- Plasma flowing along the newly opened field line forms the cusp
- The mantle is seen as those field lines then convect tailward
- Therefore, this region is characterised by
  - Tailward-flowing plasma
  - Gradual transition from sheath to lobe characteristics

john.coxon@northumbria.ac.uk

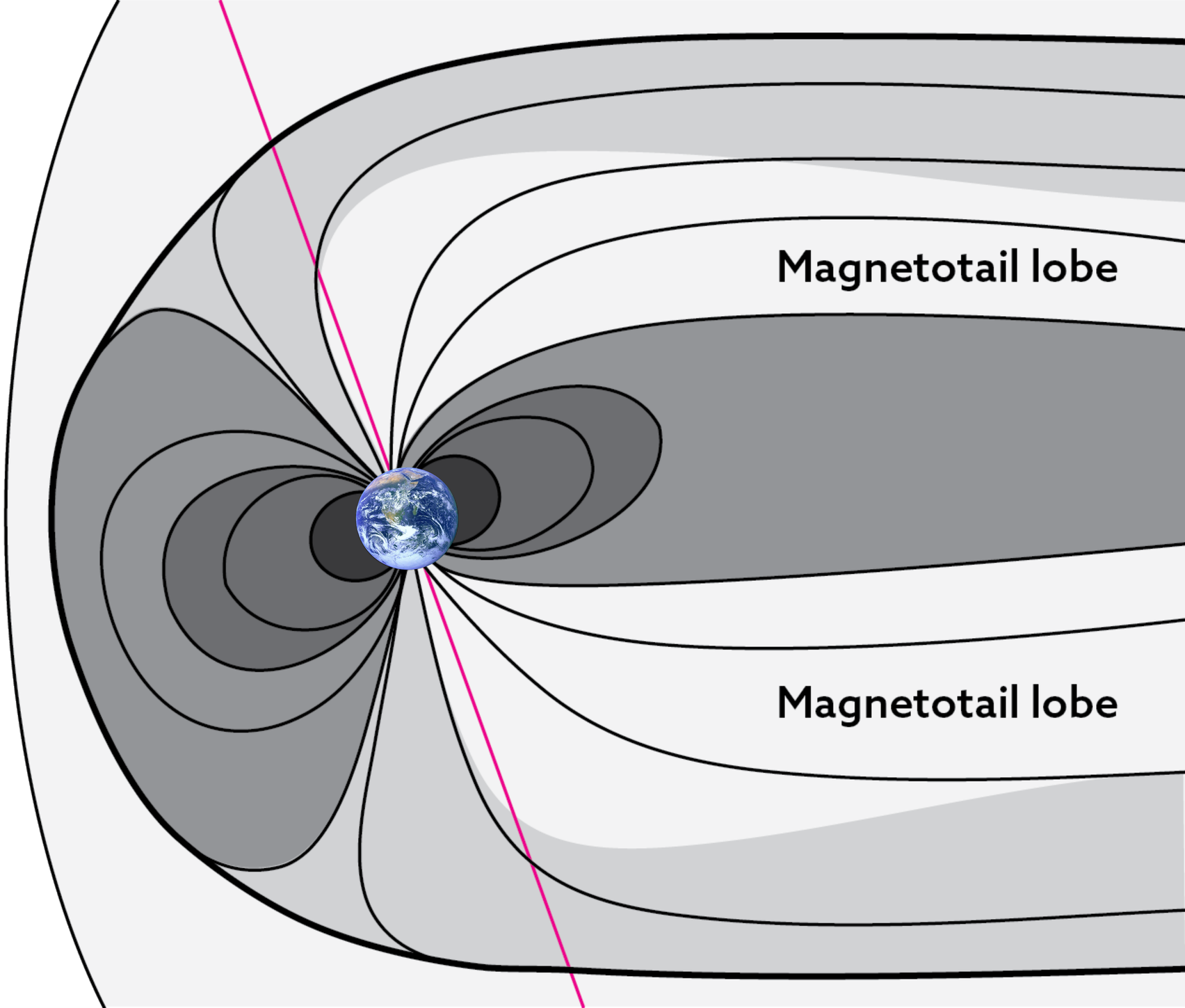
Low-latitude boundary layer (LLBL)

- Like the plasma mantle:
  - Mixture of sheath and magnetospheric plasma
- Unlike the plasma mantle:
  - In the equatorial plane
  - Has a sharp inner edge and contains plasma discontinuities; much less uniform
  - Mixed flows rather than tailward flows
  - Pictures are incredibly pixellated



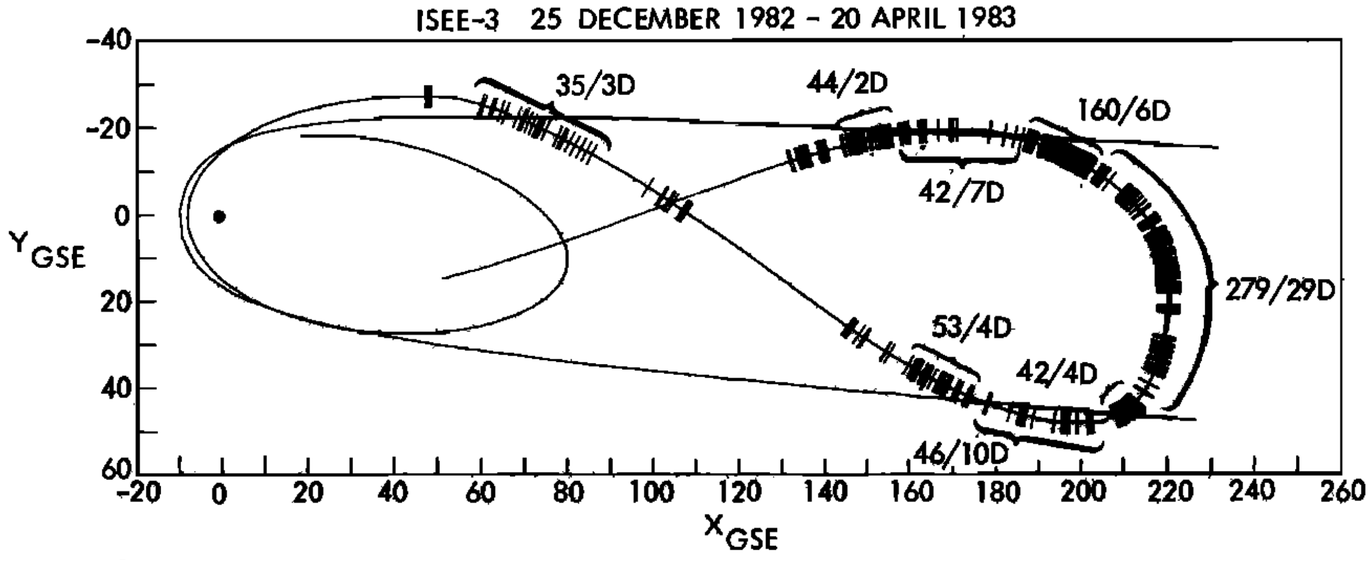
Lakhina et al. (2012)

john.coxon@northumbria.ac.uk


Magnetotail lobe
Magnetotail lobe

Magnetotail lobes

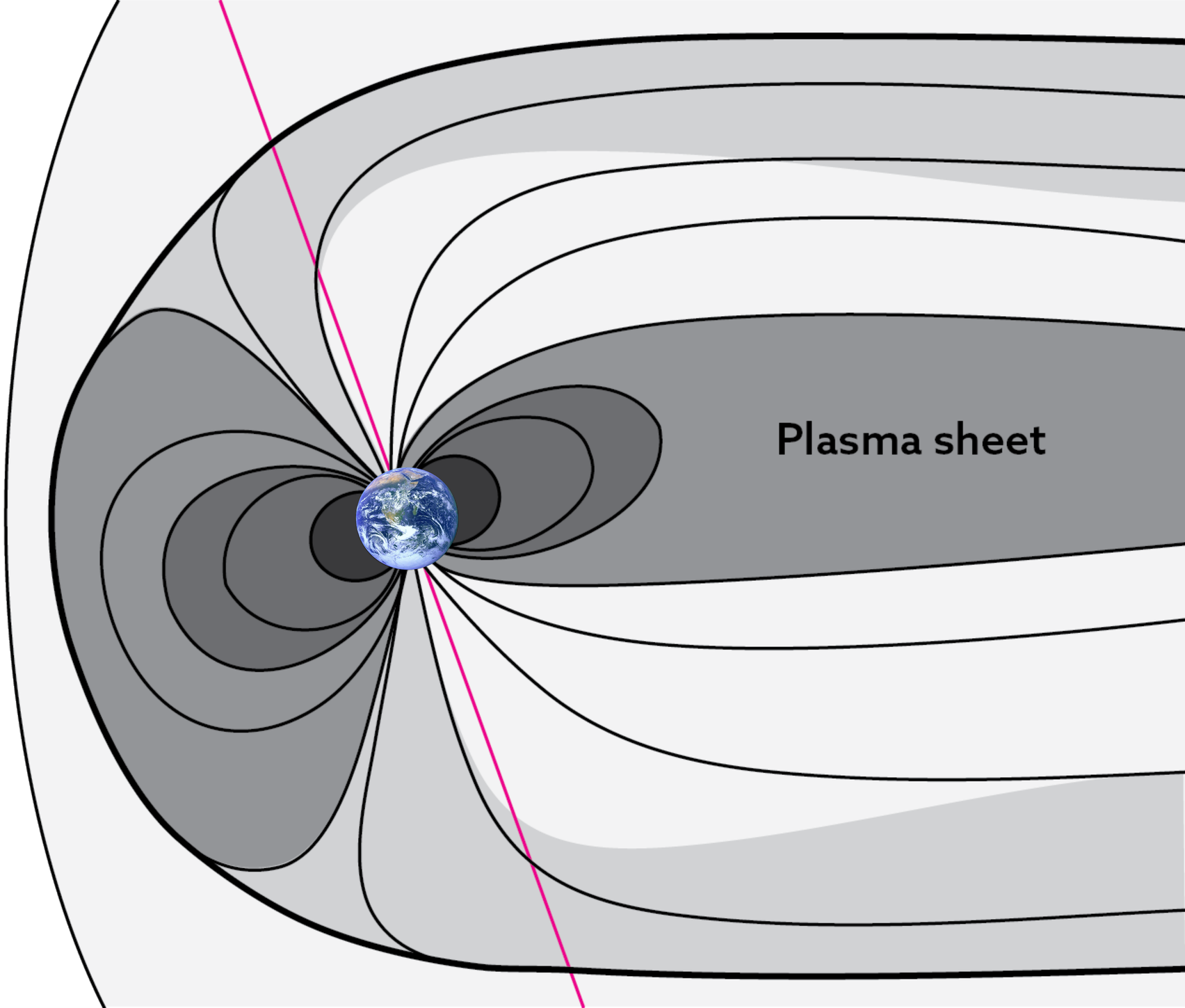
- The sun stretches open field lines at least 235 R_E downtail
- These open field lines on the nightside are the magnetotail lobes
- Hot plasma escapes, so lobes are cold, ~~lonely~~ tenuous plasma



Why didn't ISEE-3 go further downtail?

Slavin et al. (1985)

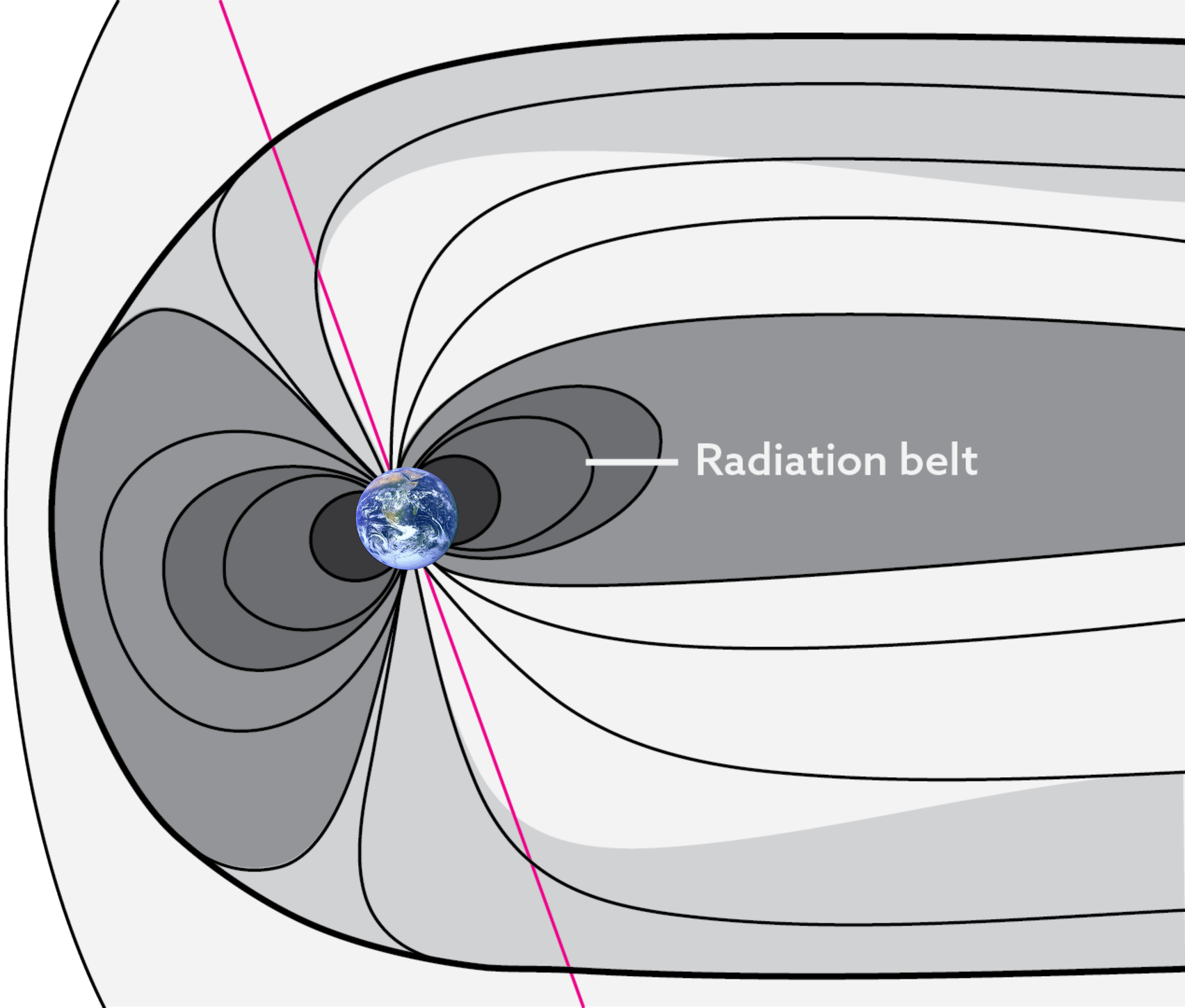
john.coxon@northumbria.ac.uk


Plasma sheet

Plasma sheet

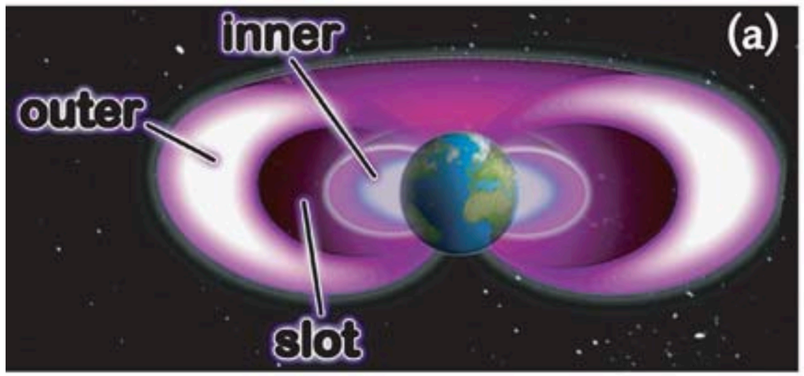
- Nightside reconnection closes field lines and accelerates plasma
- Plasma streams towards Earth along the newly closed field lines
  - Known as a particle injection
- Plasma mirrors close to the Earth, forming antisunward streams
- These streams are unstable to plasma waves
- Waves convert the streaming energy to thermal energy
- This creates the hot, dense plasma sheet

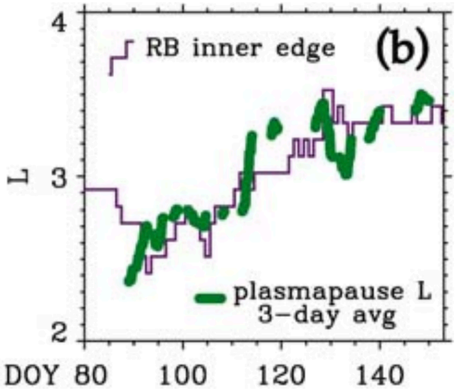
john.coxon@northumbria.ac.uk


Radiation belt

Radiation belts (the Van Allen belts)

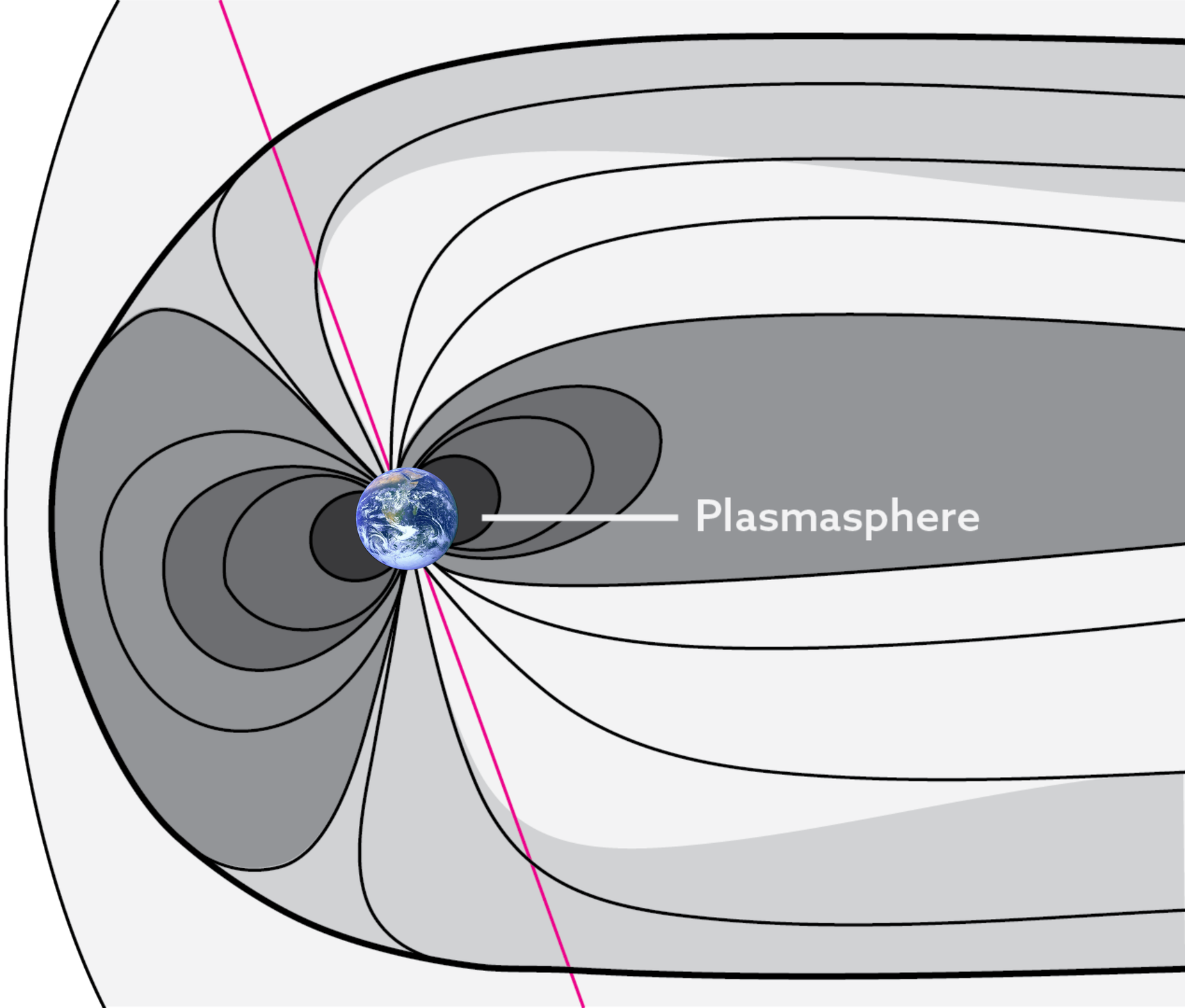
- The most energetic particles in the magnetosphere
- Electron population from direct injection from substorms
  - Then accelerated by wave-particle interactions
- Proton population from beta decay of neutrons
- Less energetic particles from the plasma sheet
- **Electron** belts are in two regions, separated by a slot





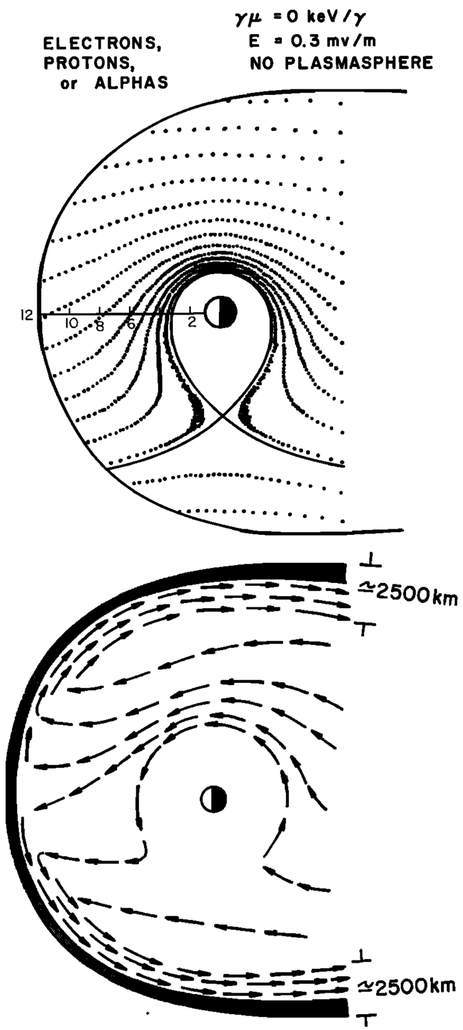
Goldstein (2006)

john.coxon@northumbria.ac.uk


Plasmasphere

We need to talk about corotation

- Up to now we've been talking in terms of convection: i.e., electromagnetic driving
- However, the atmosphere **corotates** with Earth, eastward, up to a certain altitude (3–5 R_E)
- Plasma **convects** eastward on the dawn side but westward on the dusk side
- Separatrix between the two is the plasmapause
- Leads to a dusk side bulge as shown here

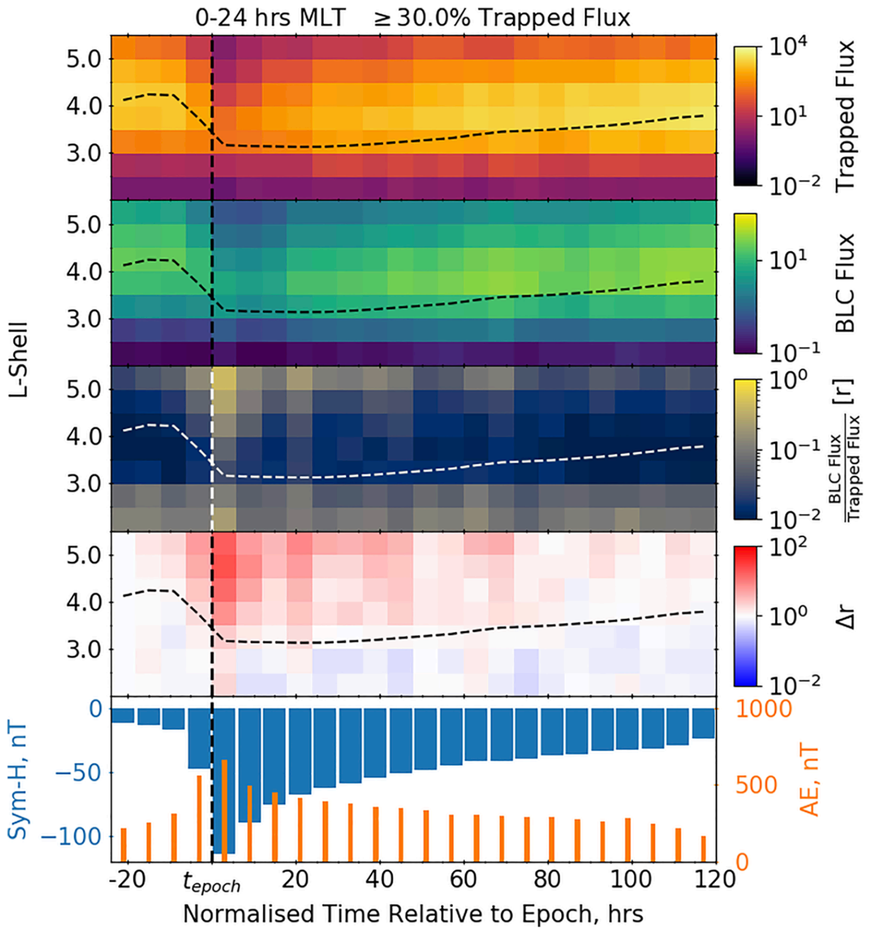


Kavanagh et al. (1968)

john.coxon@northumbria.ac.uk

Plasmasphere

- Cold plasma surrounding the Earth
- Populated by the polar wind
  - Plasma in the ionosphere has temperature higher than the gravitational energy
  - So plasma escapes upwards
- Bordered by the plasmapause
- Bounded by regions of low-density cold plasma known as ion/electron troughs

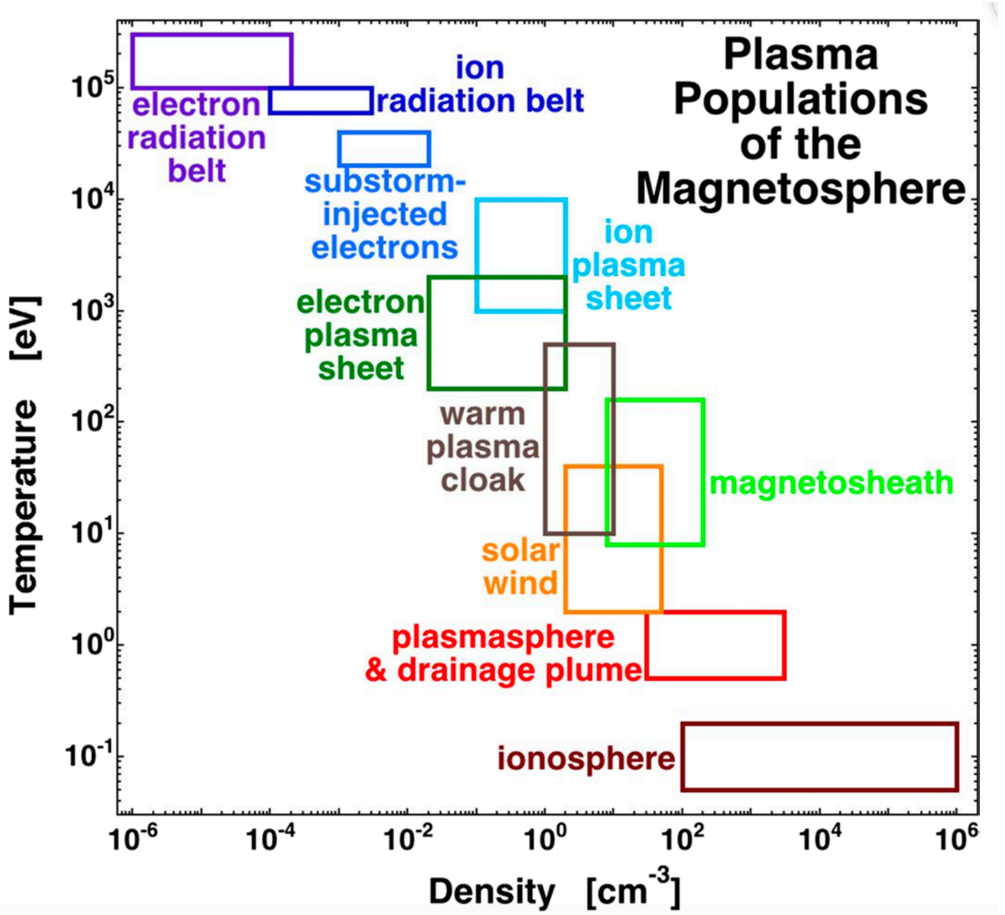


Walton et al. (2022)

john.coxon@northumbria.ac.uk

Temperature and density

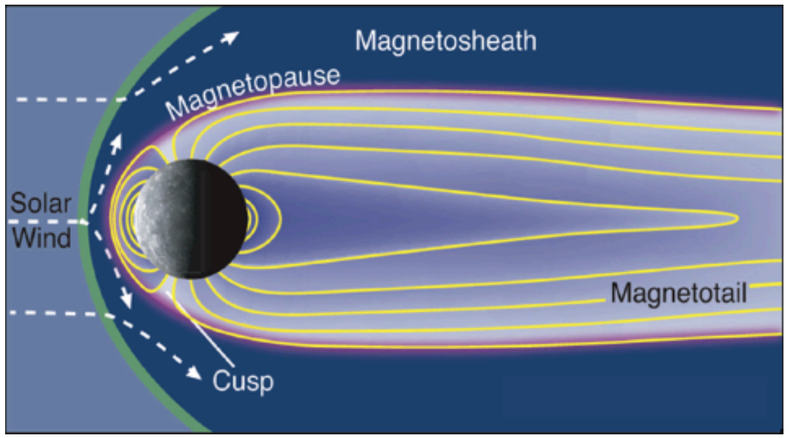
- There are many different plasma populations in the magnetosphere
- Regions I didn't mention:
  - The warm plasma cloak is colocated with the near-Earth plasma sheet
  - The drainage plume is a plasmaspheric loss mechanism to the solar wind
  - The ionosphere is the topic of Gareth Dorrian's talk tomorrow morning



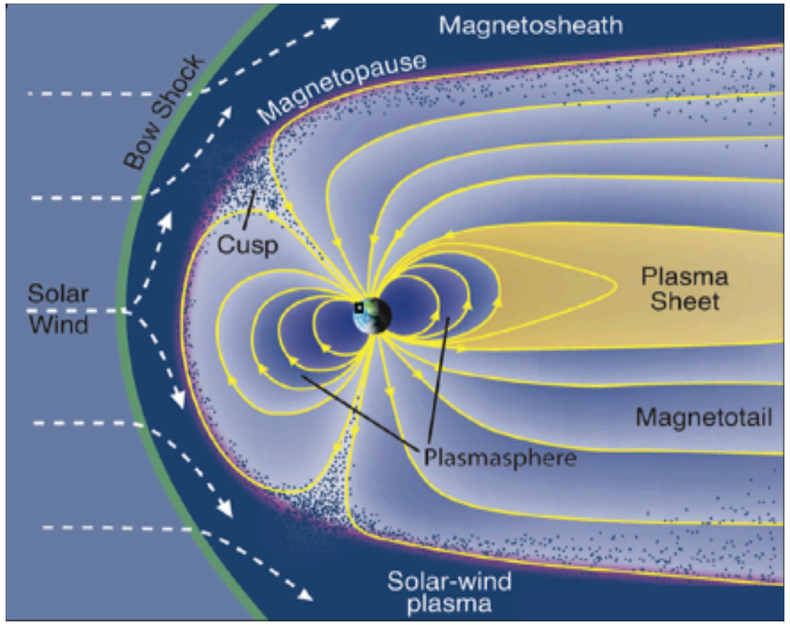
Borovsky & Valdivia (2018)

john.coxon@northumbria.ac.uk

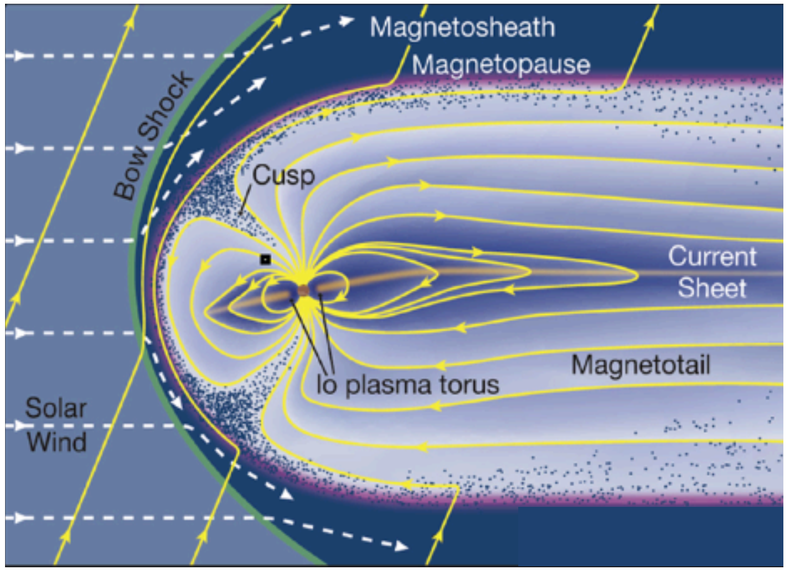
Similar but different



Mercury (~400x)



Earth (~40x)



Jupiter (~1x)

Fran Bagenal & Steve Bartlett
john.coxon@northumbria.ac.uk

Northumbria University
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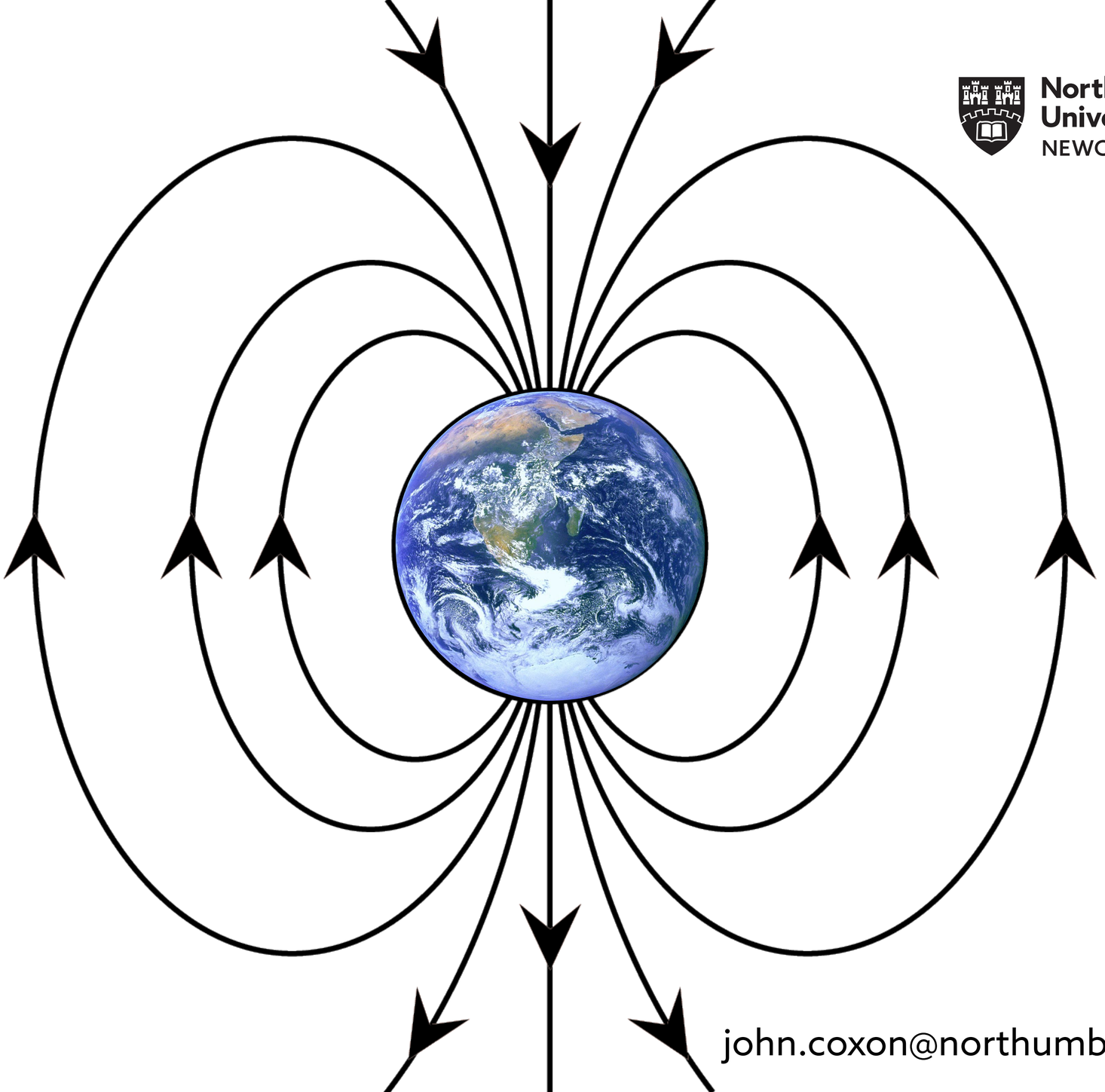
Currents in the magnetosphere

(the good bit)

john.coxon@northumbria.ac.uk

Not dipolar

- Earth's magnetic field is not dipolar
- Every departure from a dipole magnetic field requires a current to flow



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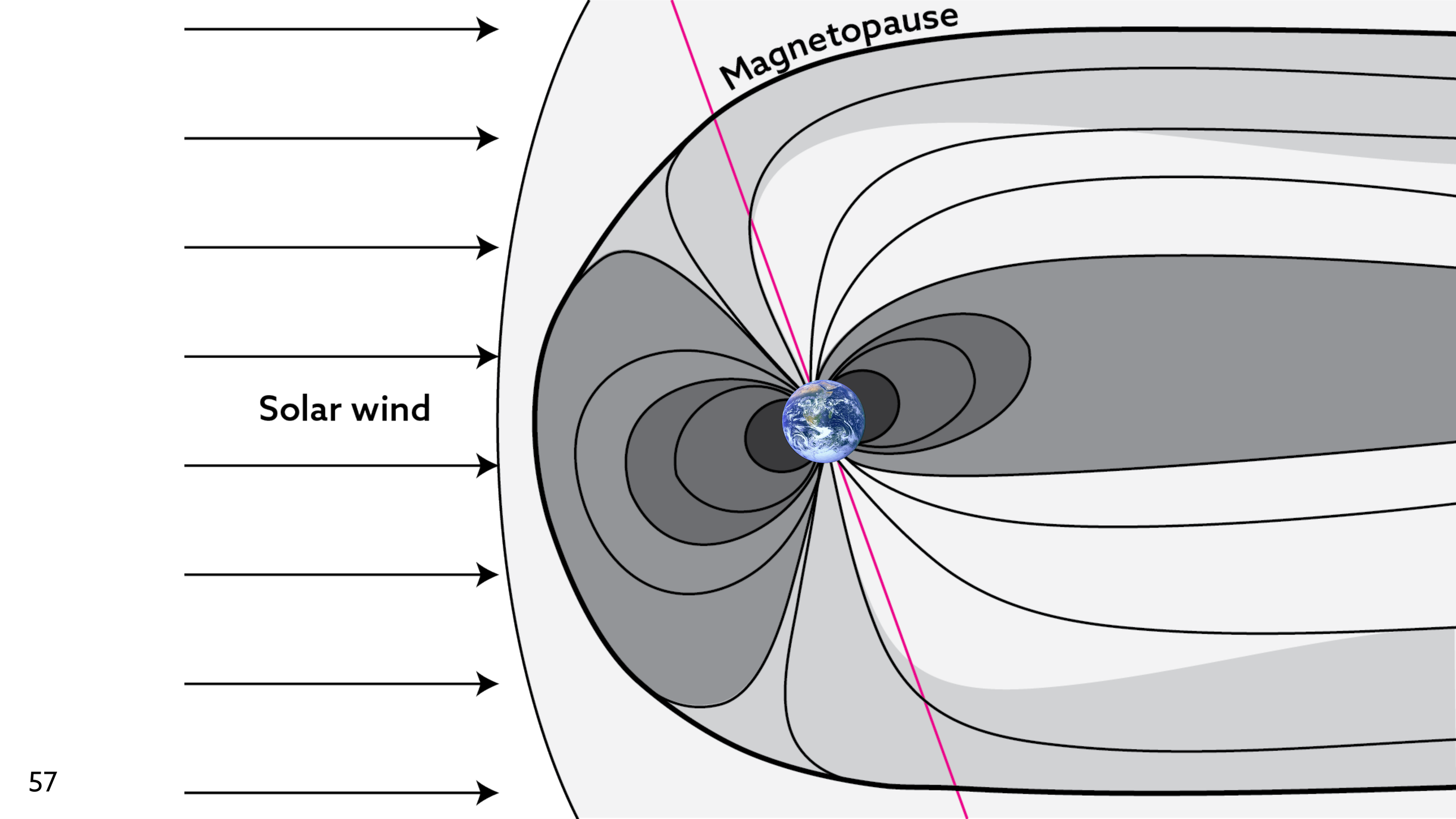
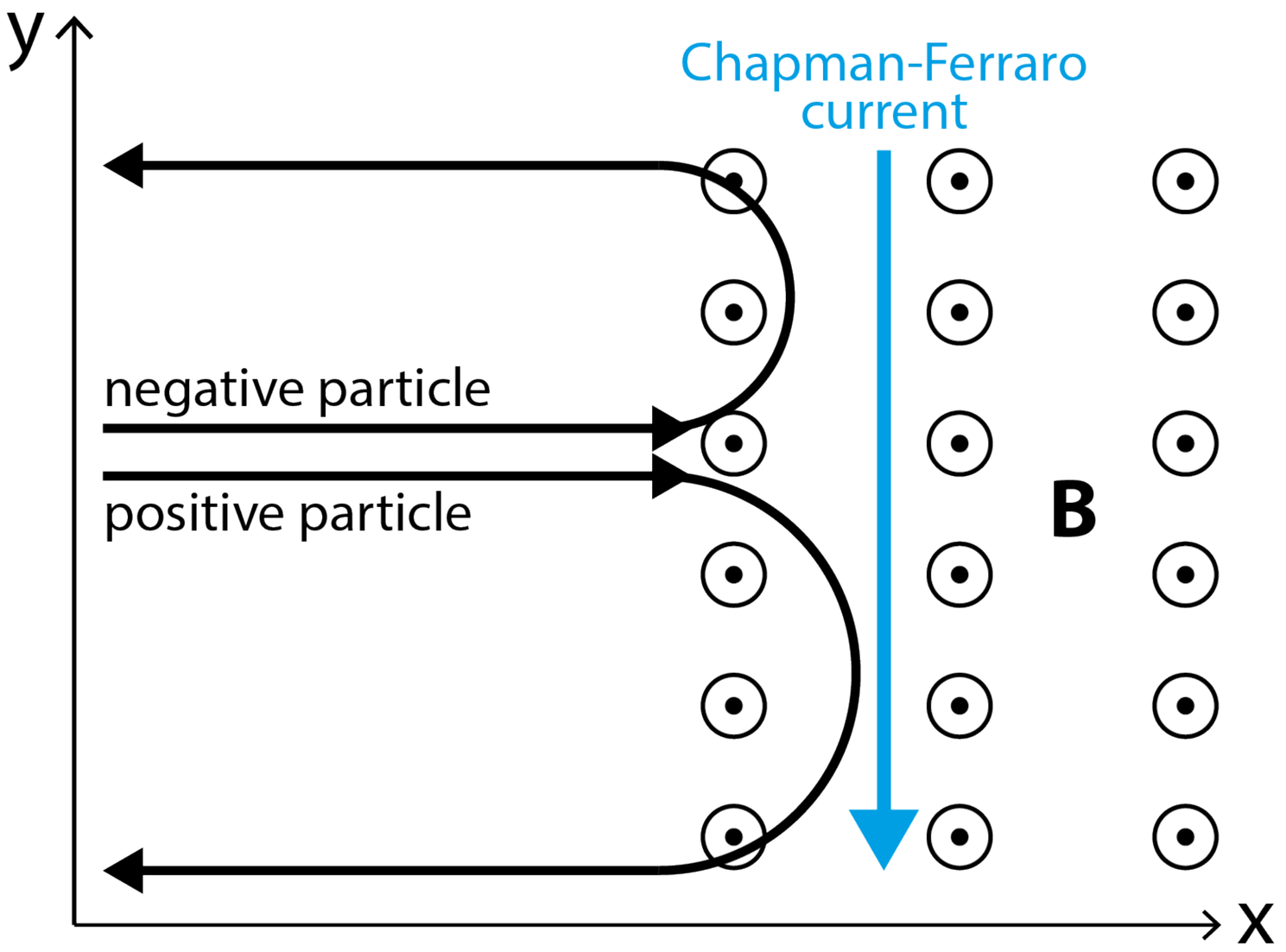
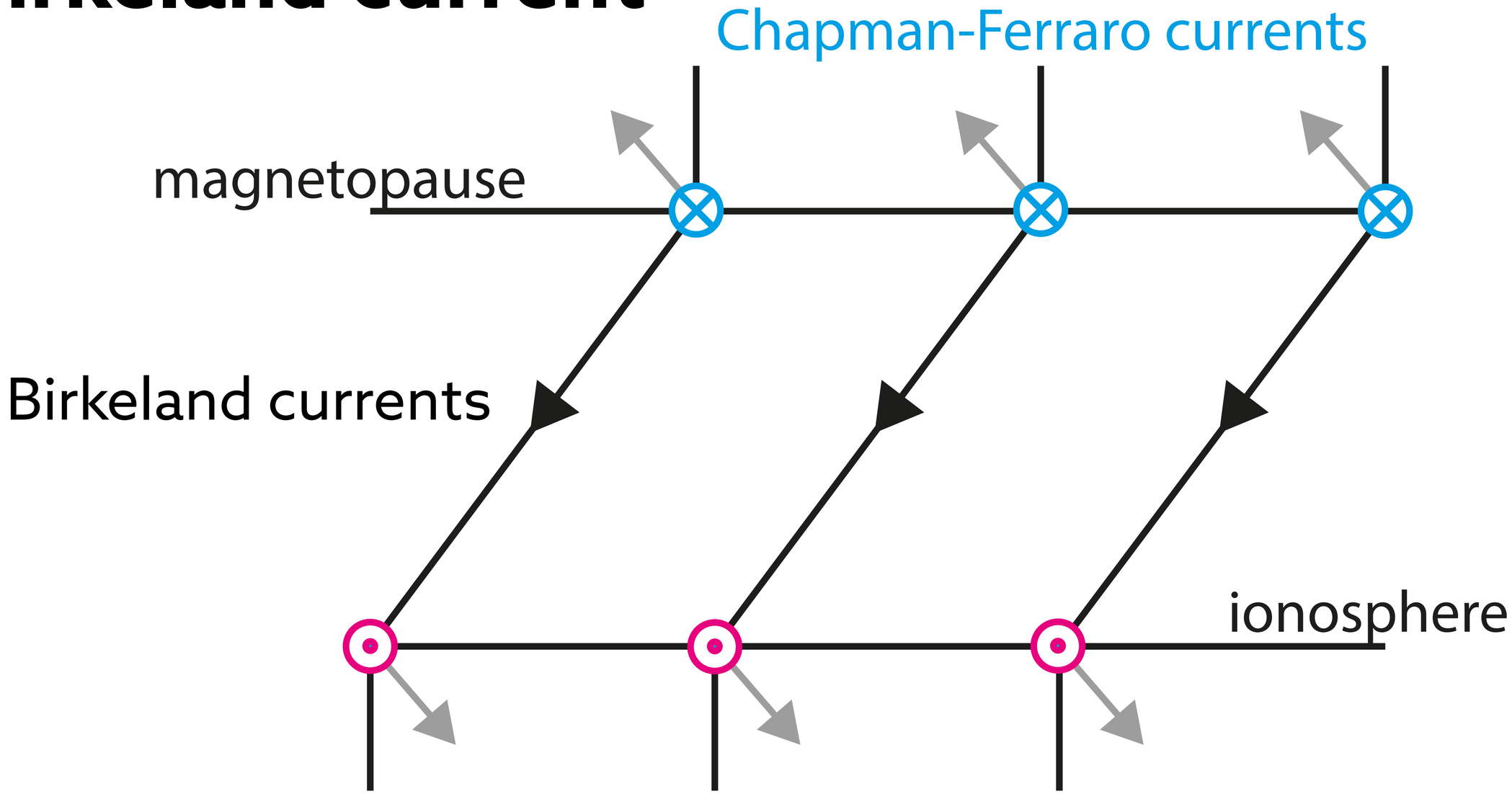

Magnetopause
Solar wind

Magnetopause



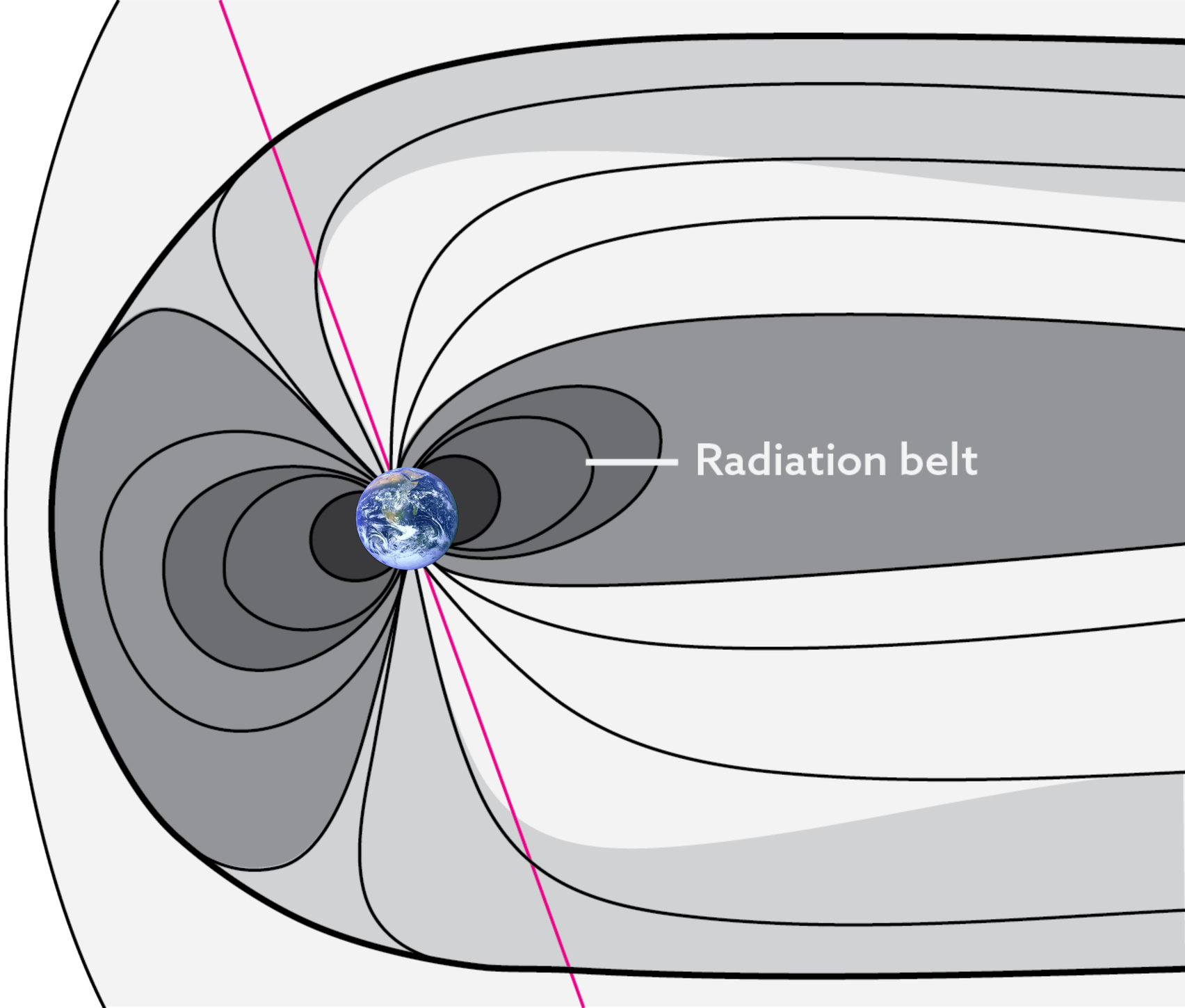
john.coxon@northumbria.ac.uk

Birkeland current

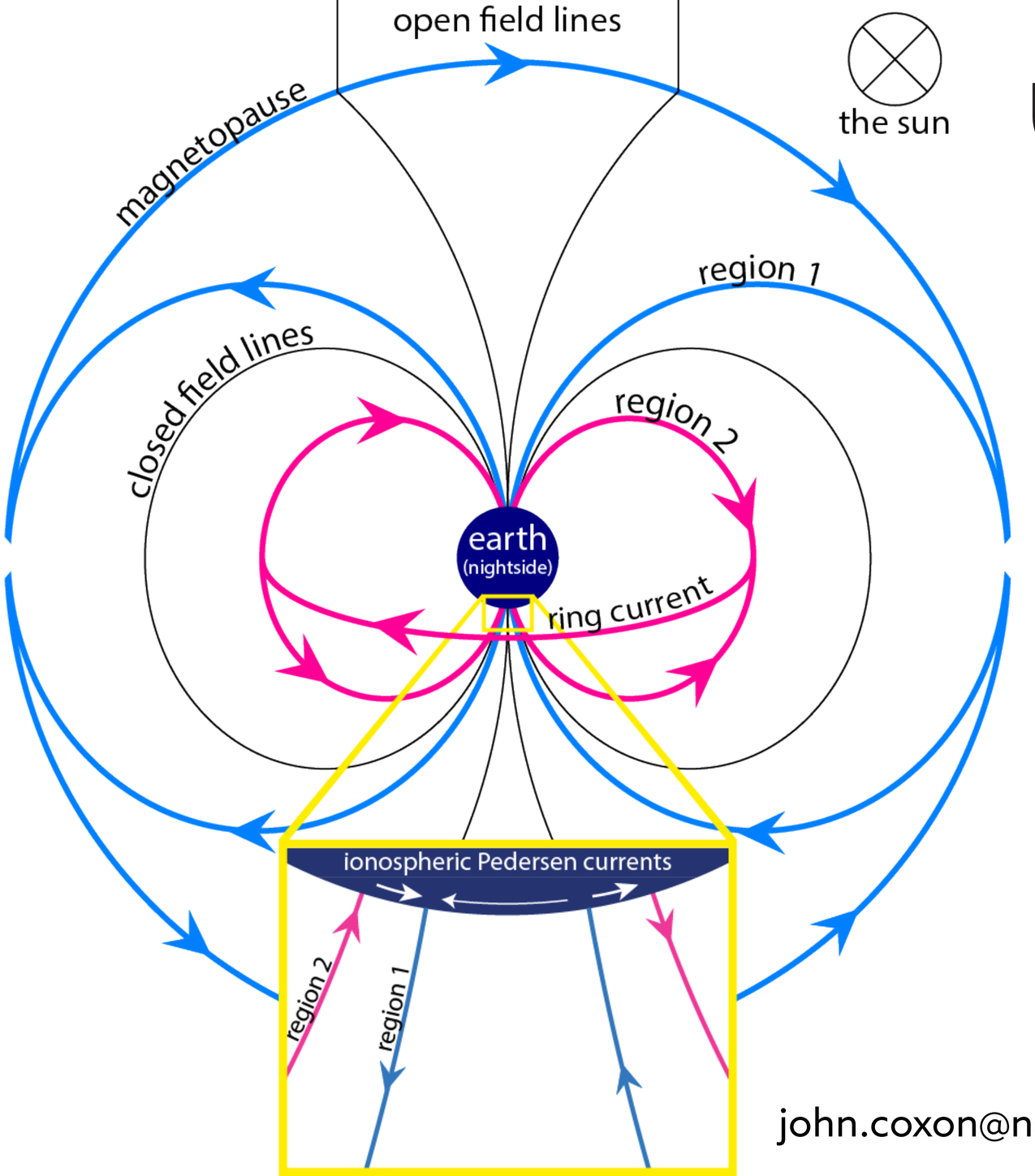


john.coxon@northumbria.ac.uk

Ring current



Ring current



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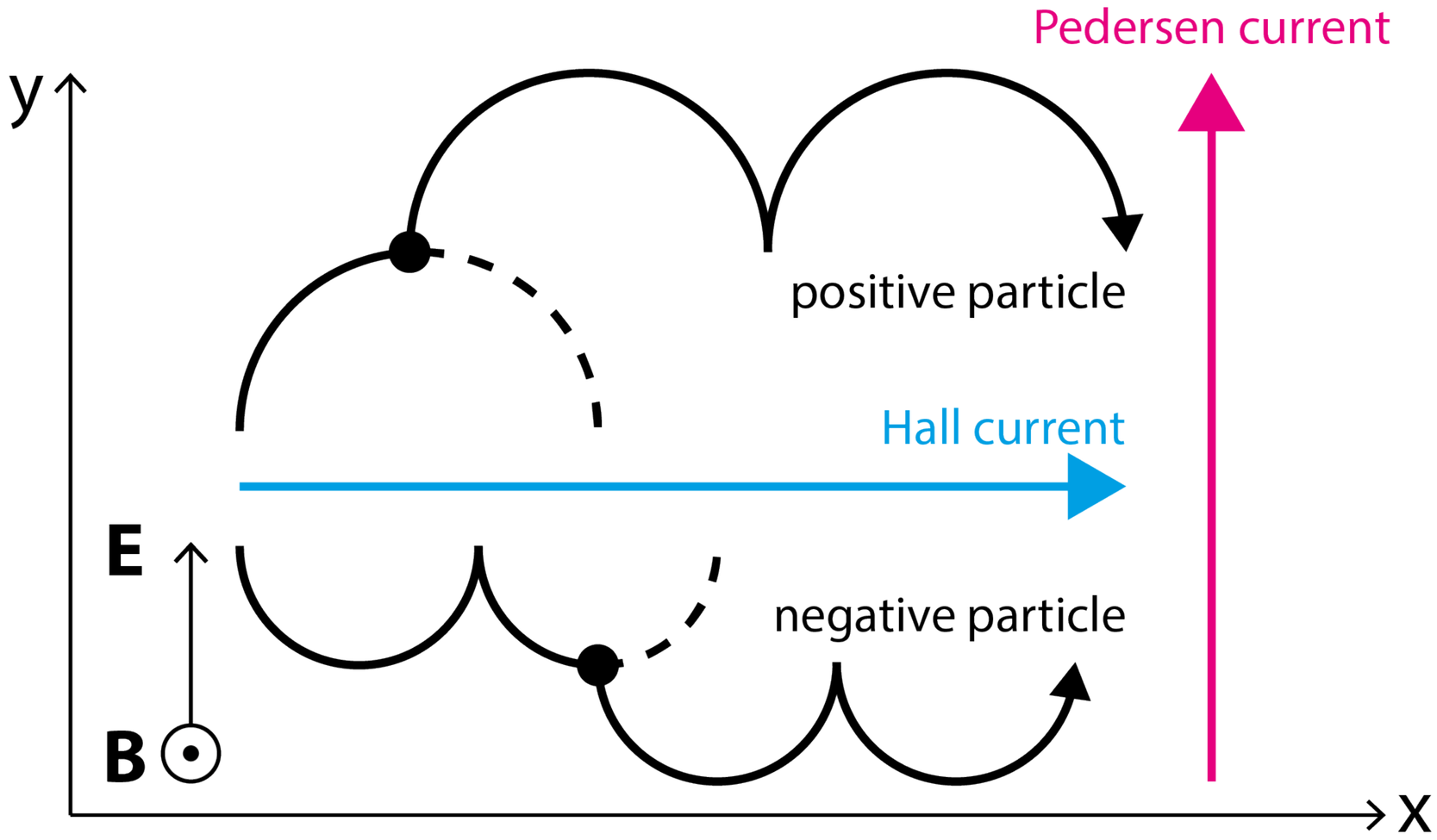
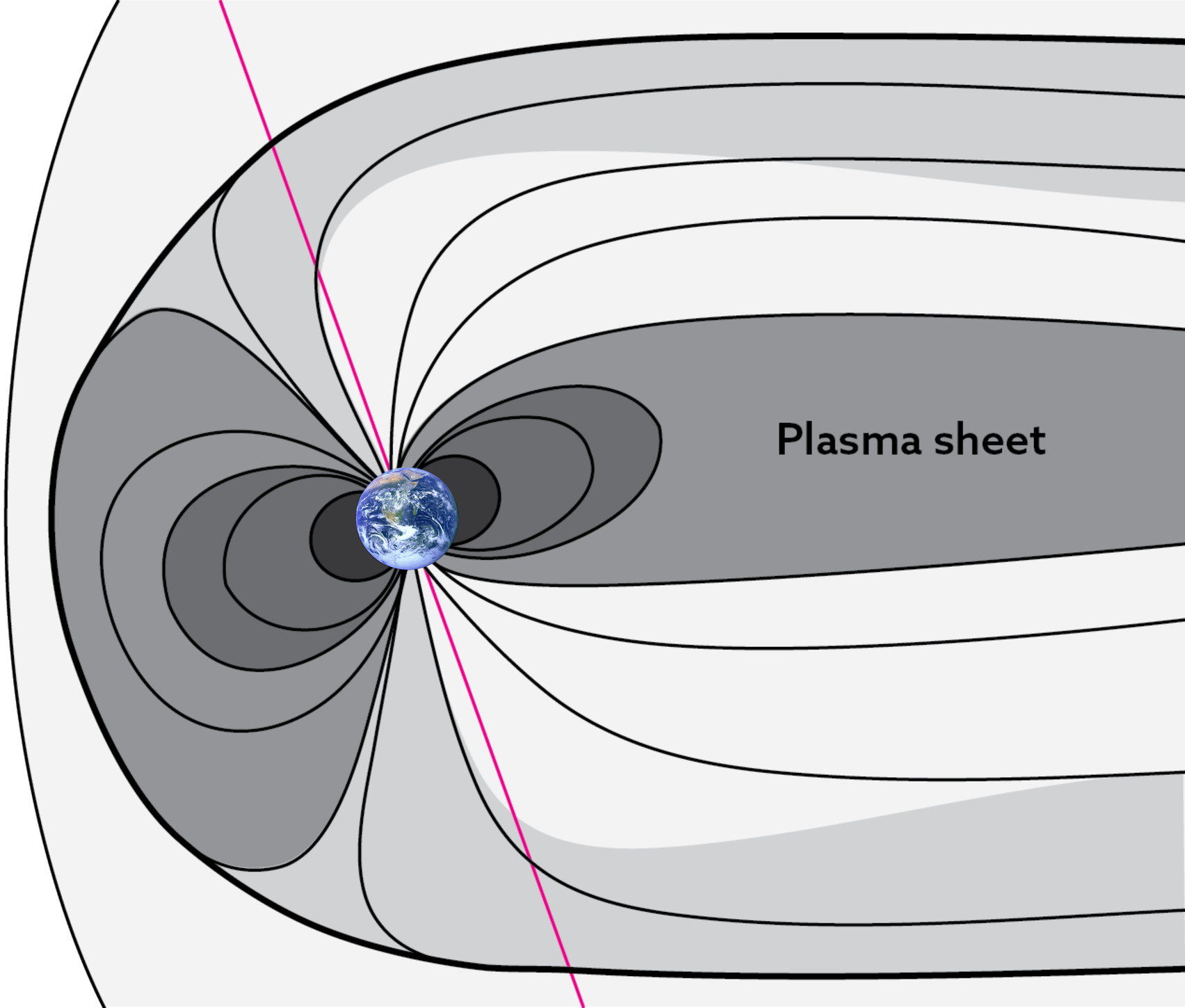
john.coxon@northumbria.ac.uk

Ionospheric current

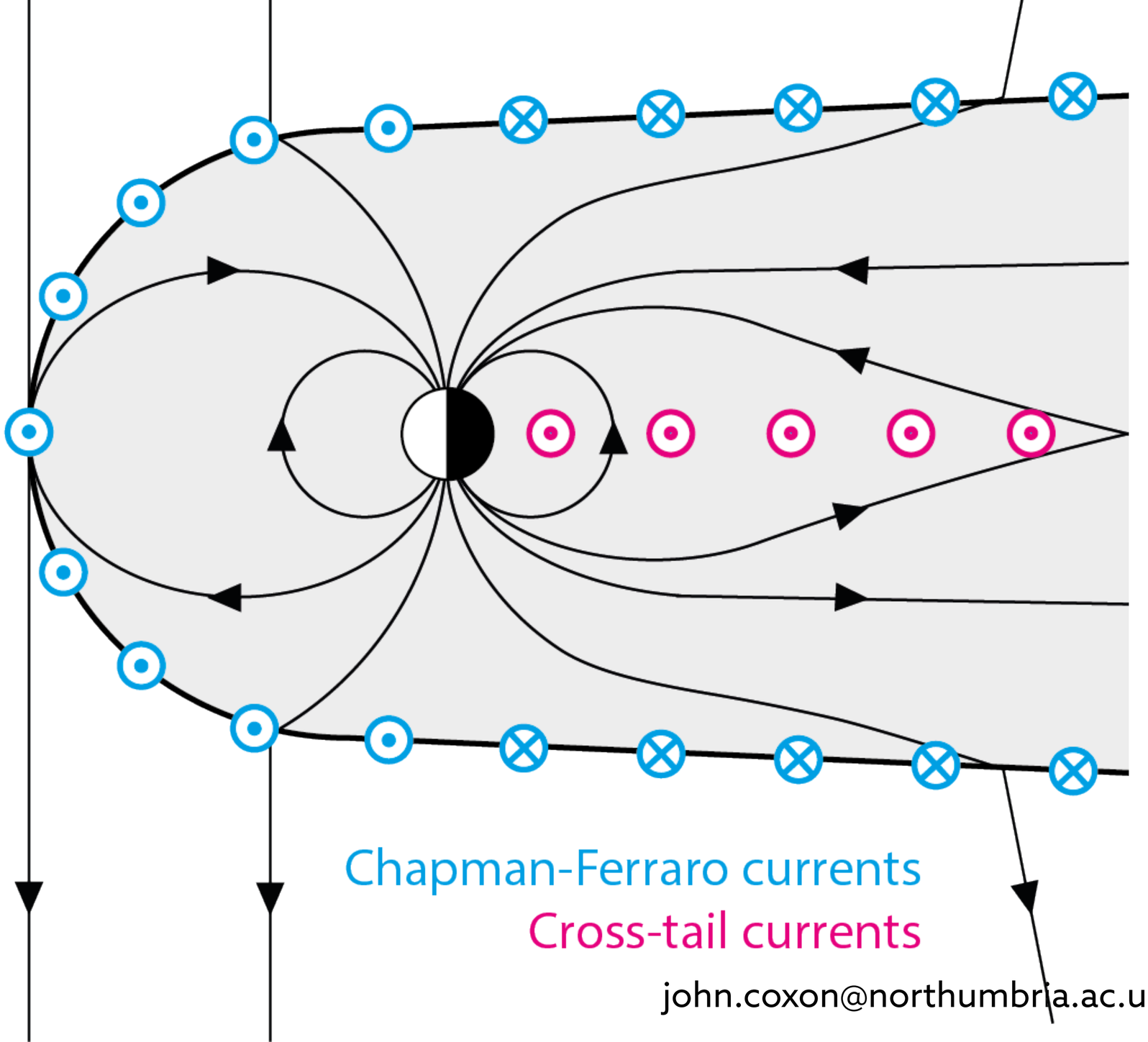


john.coxon@northumbria.ac.uk

Tail current

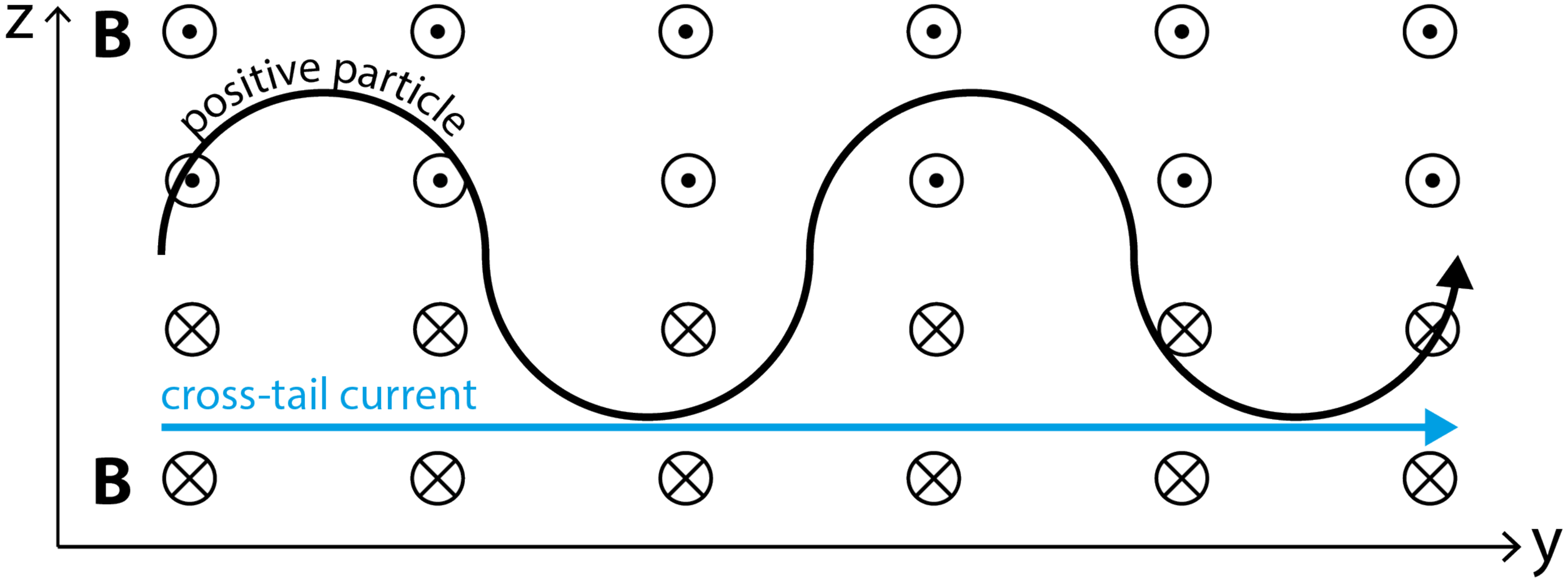


Tail current



john.coxon@northumbria.ac.uk

Tail current



john.coxon@northumbria.ac.uk

Auroras

Dan Whiter
john.coxon@northumbria.ac.uk

Magnetospheres: Find out more

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- This has been a whistle-stop tour of magnetospheres
- However, there's quite a bit more to cover...
- Recommended reading:
  - *Introduction to Space Physics* by Kivelson & Russell (eds.)
  - Milan et al. (2017) in *Space Science Reviews*
  - Borovsky & Valdivia (2018) in *Surveys in Geophysics*
  - AGU's **Geophysical Monograph Series**

john.coxon@northumbria.ac.uk