Imperial College London

The Magnetosphere

STFC Introductory Solar System Plasmas Summer School 2018

Thursday 30 August 2018, University of Exeter

Dr. Jonathan Eastwood
The Blackett Laboratory, Imperial College London, London SW7 2AZ
jonathan.eastwood@imperial.ac.uk

Imperial College London

Today's lecture: the magnetosphere

1. Basic properties of the magnetosphere
2. The structure of the magnetosphere
3. Magnetospheric dynamics
4. Aurora, substorms and storms

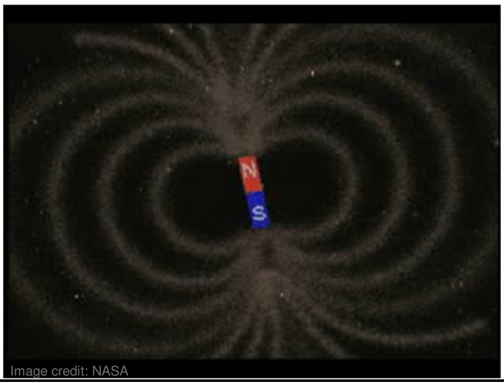
Imperial College London

1. Basic properties of the magnetosphere

1. Why is there a magnetosphere?
2. A quick tour of the magnetosphere
   1. Dayside: shock, foreshock, magnetosheath, magnetopause, cusps
   2. Inner: plasmasphere, radiation belts
   3. Tail: lobes, plasma sheet, magnetotail current sheet

Imperial College London

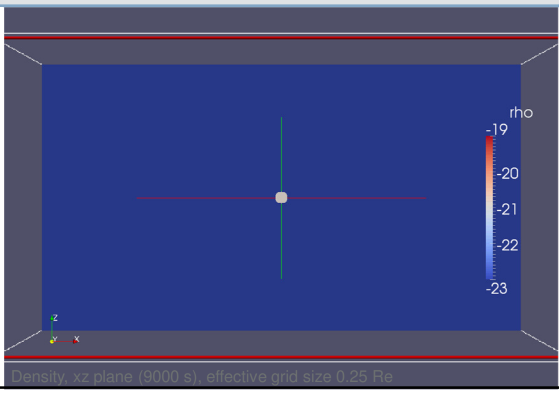
The Earth's magnetosphere



Imperial College London

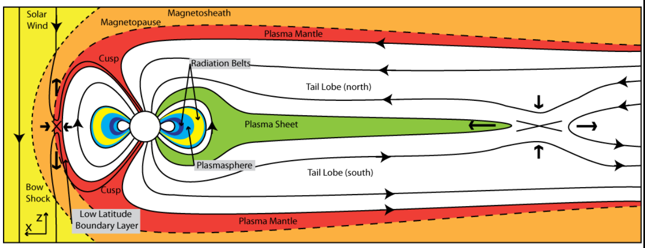
Vsw = 400 km/s, nsw = 5/cm3, B = 2nT southward

Solar wind magnetosphere simulation (Gorgon)



Imperial College London

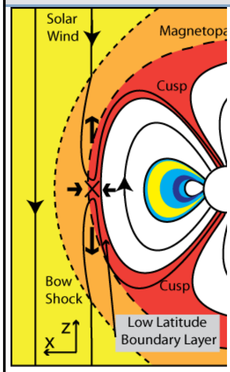
Earth's magnetosphere



Eastwood et al., Space Sci. Rev. 2015.
What controls the structure and dynamics of the Earth's magnetosphere?

Imperial College London

Earth's magnetosphere – dayside interaction

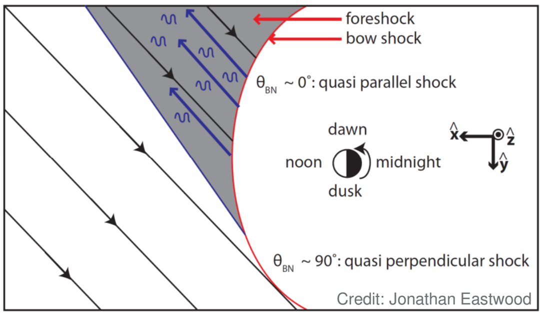


Eastwood et al., 2015.

- **Foreshock (not shown)** Backstreaming particles, waves and particle acceleration
- **Bow shock** Exists to slow and process the flow of solar wind around the magnetosphere
- **Magnetosheath** Subsonic, shocked, heated turbulent flow
- **Magnetopause** Also a current layer ("Chapman-Ferraro currents")
- **Low latitude boundary layer (LLBL)** Cushion of plasma on magnetospheric side of magnetopaused, formed by a variety of processes (e.g. diffusion)
- **Cusps** Consequence of field topology. Separates day and nightside. Weak field allows solar wind to penetrate to the ionosphere *Very important for open magnetosphere*

Imperial College London

The foreshock (for typical Parker spiral IMF)

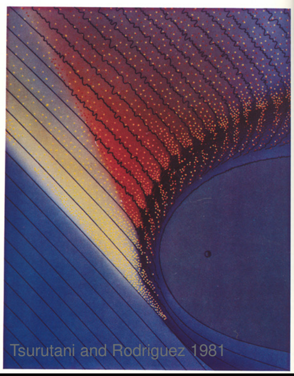


Credit: Jonathan Eastwood

Imperial College London

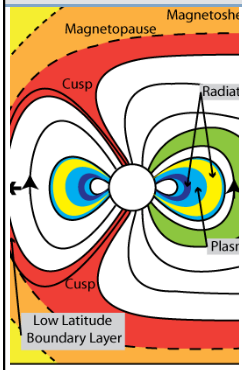
The bow shock

- Quasi-perpendicular shock (dusk flank)
  - Stable transition
  - Steep localised rise in the magnetic field strength
  - *shock ramp*
- Quasi-parallel shock (dawn flank)
  - Unsteady, continuously forming and re-forming in a cyclical manner as sharp transitions alternate with more extended ones.
  - Shock transition is a broad (1-2 Earth radii thick), turbulent region.


Tsurutani and Rodriguez 1981

Imperial College London

Earth's magnetosphere – inner magnetosphere



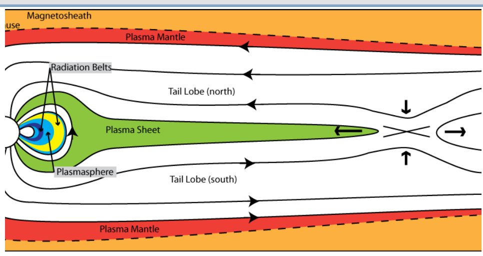
- **Magnetic field** Essentially dipolar
- **Plasmasphere** Cool plasma formed by the polar wind, (upper ionospheric plasma whose temperature is sufficient to escape Earth)
- **Radiation belts** Trapped energetic particles which are co-located with the plasmasphere
- **Auroral Oval (not shown)** Marks the boundary of the closed field lines in the inner magnetosphere.
- **Polar Cap** Region inside the auroral oval connecting to the magnetotail lobes

Eastwood et al., 2015

Imperial College London

Eastwood et al., 2015

Earth's magnetosphere – magnetotail

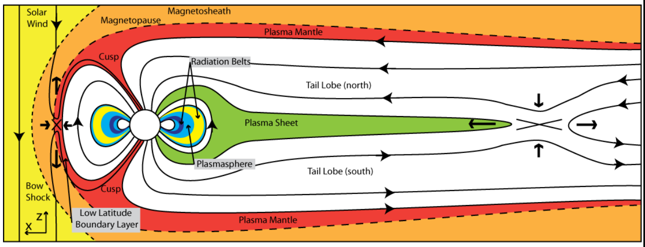


- **Plasma mantle** Tailward extent of LLBL
- **Tail Lobes** Magnetic flux connected to Earth at one end only, devoid of plasma
- **Plasma sheet** Relatively hot plasma on closed field lines sandwiched between lobes
- **Neutral sheet (not shown)** The current sheet which separates the oppositely directed

Imperial College London

Eastwood et al., 2015

Earth's magnetosphere – simplified cartoon



- **Daily and annual variation:**

Earth's rotation axis is tilted 23° from z_{GSE} , magnetic axis ~11 ° from rotation axis

- **Solar wind varies continuously on time scales of minutes to hours**:

Boundaries and regions are *not stationary* : considerable dynamical behaviour.

- **Two regions of magnetic reconnection are shown (Bz *southward*)**

This aspect (the open magnetosphere) is discussed in the next section.

Imperial College London

2. The structure of the magnetosphere

1. Dayside magnetopause pressure balance
2. Inner magnetosphere: L shell
3. Radiation belts
4. Current systems

Imperial College London

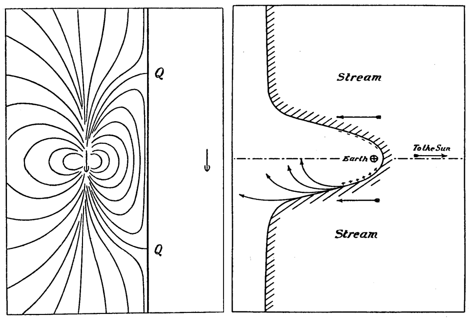
Interaction of a corpuscular stream with Earth's magnetic field

Chapman and Ferraro, 1930s, Chapman and Bartels, 1940

Approaching plasma cloud = perfectly conducting 'wall'

→ Method of images explains flattening of Earth's field

→ Later realised that Earth confined to a cavity and that solar wind was continuous



Imperial College London

Magnetopause: a topological, pressure-balanced boundary

- The Earth's magnetic field carves a "bubble" in the solar wind – the magnetosphere
- Apply frozen in field theorem
  - Magnetopause separates solar wind and magnetosphere
  - Solar wind ram pressure compresses Earth's field
  - **Pressure balance** is main factor controlling size and shape of magnetosphere
- To first order, it is "closed"
  - Bow shock forms ahead of magnetosphere
  - Shocked solar wind flows around magnetosphere in the magnetosheath

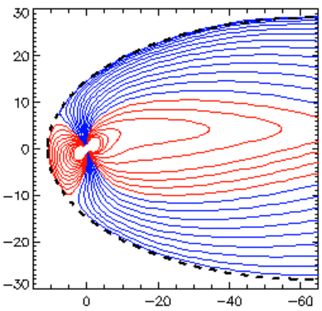
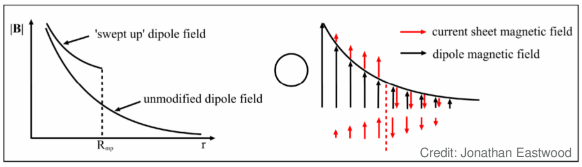


Image Credit N. Tsyganenko

Imperial College London

Magnetopause – simple model

Consider interaction of dipole with ***unmagnetised*** solar wind



Credit: Jonathan Eastwood

$$\kappa \rho u_{sw}^2 = \frac{B^2}{2\mu_0}$$ ← *B = 2 x B_{dipole}*

$$r_{MP} = R_E \left(\frac{2B_E^2}{\mu_0 \kappa \rho u_{sw}^2} \right)^{1/6}$$

K is efficiency factor

Imperial College London

Magnetospheres in the solar system

Planet	Distance from Sun (AU)	Magnetic Moment (M_E)	Planet Radius	Solar wind ram pressure (ρu^2)	Calculated Magneto-pause distance(*)	Actual Magneto-pause distance
Mercury	0.4	4×10^{-4}	2,440 km	20 nPa	1.25 R_m	1.5 R_m
Earth	1	1	6,370 km	3.0 nPa	9 R_e	10 R_e
Jupiter	5.2	1.8×10^4	69,911 km	0.1 nPa	38 R_j	70 R_j
Saturn	9.5	580	60,268 km	30 pPa	17 R_s	21 R_s
Uranus	19.2	50	25,559 km	8 pPa	22 R_u	27 R_u
Neptune	30.1	24	24,764 km	3 pPa	21 R_n	26 R_n

Earth dipole moment: $M_E = B_0 \times R_0^3$ = 31,000 nT x (6,370 km)$^3 \approx 8 \times 10^{15}$ Am^2
(*) Magnetopause distance calculation based on balance $\rho u_{SW}^2 = B^2 / (2\mu_0)$

Magnetospheres

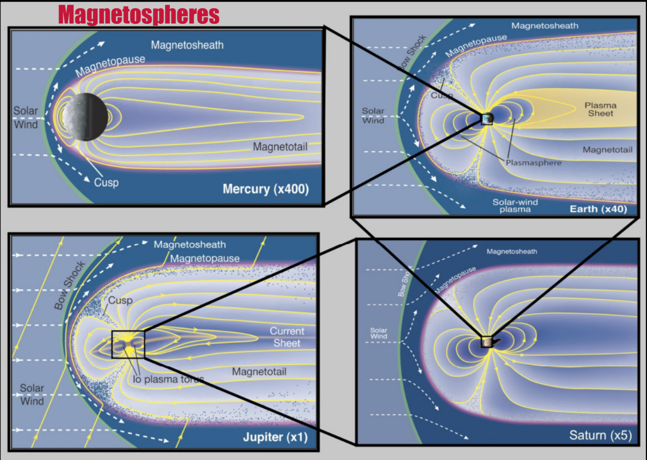


Image credit: Fran Bagenal/ Steve Bartlett, LASP, Colorado

Imperial College London

The terrestrial dipole field

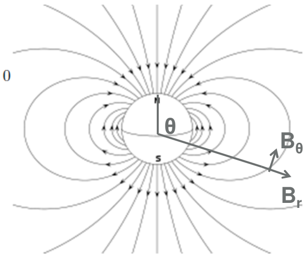
Earth's magnetic field given by:

$$B_r = \frac{-2M\cos\theta}{r^3} \qquad B_\theta = \frac{-M\sin\theta}{r^3} \qquad B_\phi = 0$$

θ is magnetic co-latitude (0 at north pole)
φ is longitude

M is dipole moment (B_E = 31,000 nT at R_E = 6380 km)

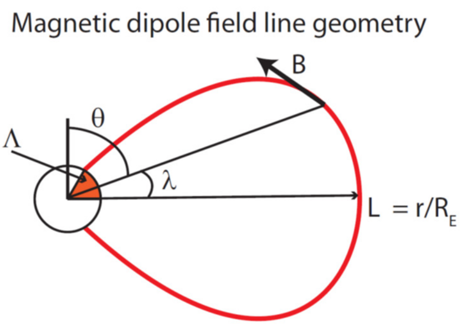
$$M = B_E R_E^3$$



Field strength is therefore: $B = B_E\left(\frac{R_E}{r}\right)^3\sqrt{3\cos^2\theta+1}$

Imperial College London

Magnetic dipole field line geometry



Credit: Jonathan Eastwood

Imperial College London

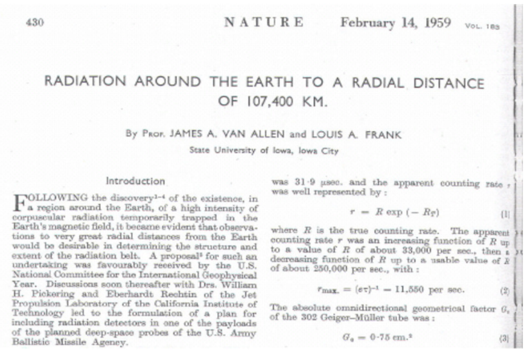
Explorer 1 – the first space plasma physics mission

William Pickering, director of JPL (designed and built the satellite)
James Van Allen, directed the design and construction of the instruments
Wernher von Braun, designed and built the Jupiter-C rocket

Imperial College
London

Explorer 1

Discovered belts of particle radiation around the Earth: the Van Allen radiation belts



430 NATURE February 14, 1959 Vol. 183

RADIATION AROUND THE EARTH TO A RADIAL DISTANCE OF 107,400 KM.

By Prof. JAMES A. VAN ALLEN and LOUIS A. FRANK

State University of Iowa, Iowa City

Introduction

FOLLOWING the discovery[1-4] of the existence, in a region around the Earth, of a high intensity of corpuscular radiation temporarily trapped in the Earth's magnetic field, it became evident that observations to very great radial distances from the Earth would be desirable in determining the structure and extent of the radiation belt. A proposal[5] for such an undertaking was favourably received by the U.S. National Committee for the International Geophysical Year. Discussions soon thereafter with Drs. William H. Pickering and Eberhardt Rechtin of the Jet Propulsion Laboratory of the California Institute of Technology led to the formulation of a plan for including radiation detectors in one of the payloads of the planned deep-space probes of the U.S. Army Ballistic Missile Agency.

was 31·9 μsec. and the apparent counting rate r was well represented by:

$$r = R \exp(-R\tau) \quad (1)$$

where R is the true counting rate. The apparent counting rate r was an increasing function of R up to a value of R of about 33,000 per sec., then a decreasing function of R up to a usable value of R of about 250,000 per sec., with:

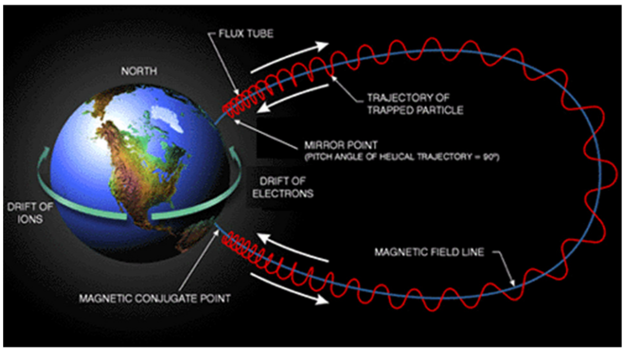
$$r_{max.} = (e\tau)^{-1} = 11{,}550 \text{ per sec.} \quad (2)$$

The absolute omnidirectional geometrical factor G_o of the 302 Geiger–Müller tube was:

$$G_o = 0{\cdot}75 \text{ cm.}^2 \quad (3)$$

Imperial College
London

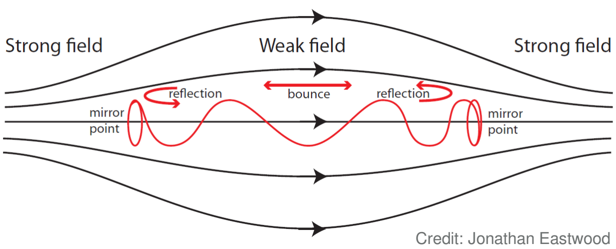
Inner magnetosphere particle motion



http://pluto.space.swri.edu/image/glossary/pitch.html

Imperial College
London

Magnetic bottle



Credit: Jonathan Eastwood

Imperial College London

Particle drifts – general force drift

The examples of drifts which plasma can experience in the presence of B and E fields can be formulated in more general form:

Assuming a uniform external force **F** (independent of v, r) then the drift motion becomes

$$\boxed{\mathbf{v_f} = \frac{1}{q}\frac{\mathbf{F}\times\mathbf{B}}{B^2}}$$

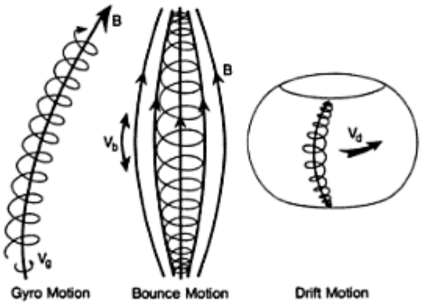
Example: curvature and gradient drift:

$$v_{\nabla B} = \frac{mv_\perp^2}{2qB}\frac{\boldsymbol{B}\times\nabla B}{B^2}$$

$$v_C = \frac{mv_\parallel^2}{qB^2}\frac{\boldsymbol{r_C}\times\boldsymbol{B}}{r_C^2}$$

Imperial College London

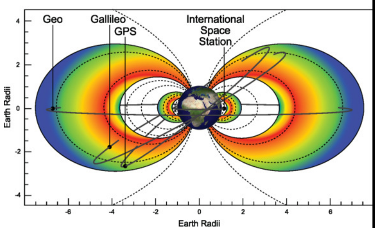
Particle motion in the radiation belts

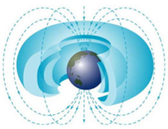


Imperial College London

Radiation belts

- **Inner radiation belt** (discovered by Van Allen)
  - extends ~1 R_E radius above the equator
  - consists of very energetic protons,
  - by-product of cosmic ray ions colliding with atmosphere.
  - very stable
- **Outer radiation belt**
  - fluctuates considerably (due to magnetospheric activity)
  - 'killer electrons
- **Ring current**,
  - Contains ions and electrons of much lower energy, colocated with Outer Belt

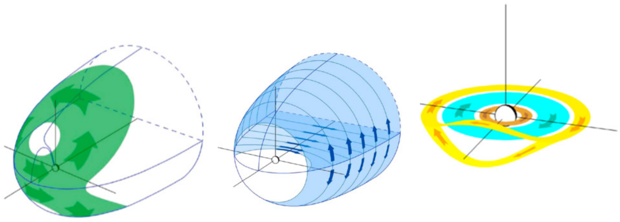




Credit: fp7-spacecast.eu Richard Horne

Imperial College London

Examples of magnetospheric current systems



Magnetopause current | Tail current | Ring current

Credit: Ganuskina et al., 2018

Imperial College London

3. Magnetospheric dynamics

1. Magnetic reconnection
2. The open magnetosphere – southward IMF
3. Convection and corotation
4. Northward IMF

Imperial College London

Magnetic reconnection

In most regions of astrophysical plasma, magnetic diffusivity is low

- magnetic field is "frozen in"

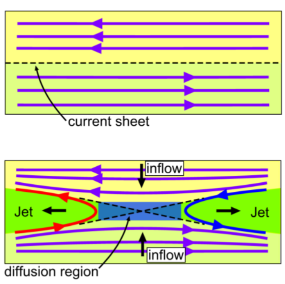
Different regions of plasma cannot interpenetrate

- boundary layers form
- magnetic energy can be stored

Magnetic Reconnection may occur within the boundary layer

- Energy released
- Changed topology
- Particle acceleration

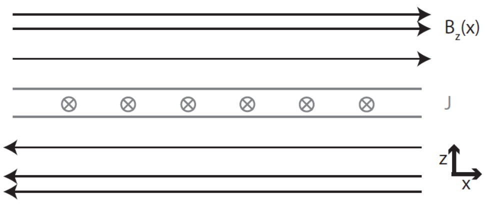
The central diffusion region plays a crucial role, because this is where the plasma demagnetises.



Eastwood, PTRSA, 2008

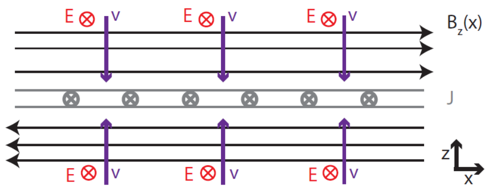
Imperial College London

Current sheet



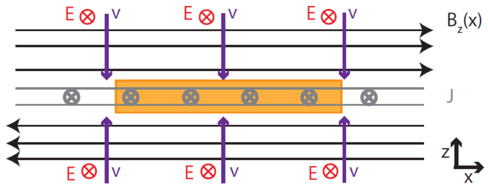
Imperial College London

Compressed current sheet



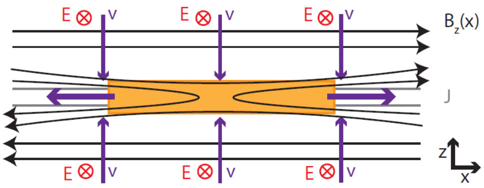
Imperial College London

Formation of a diffusion region



Imperial College London

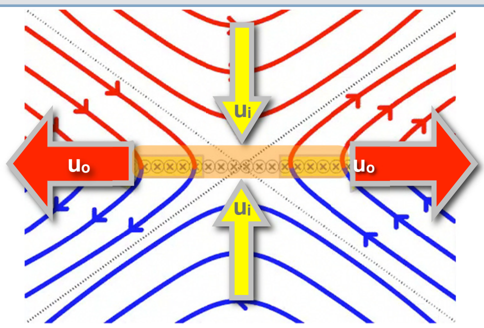
Magnetic reconnection



Credit: Jonathan Eastwood

Imperial College London

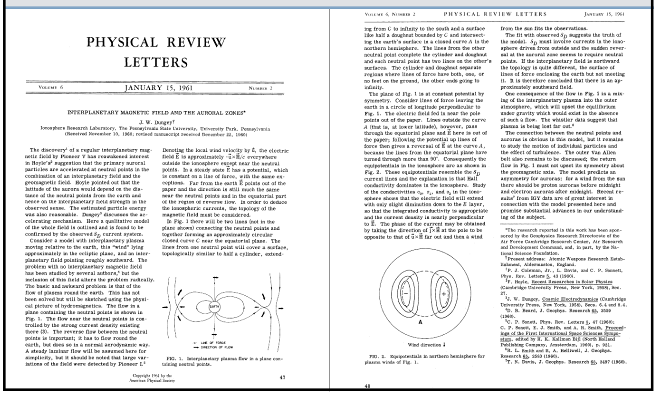
Reconnection animation



Credit: Wikimedia

Imperial College London

The open magnetosphere – Dungey, 1961


PHYSICAL REVIEW LETTERS

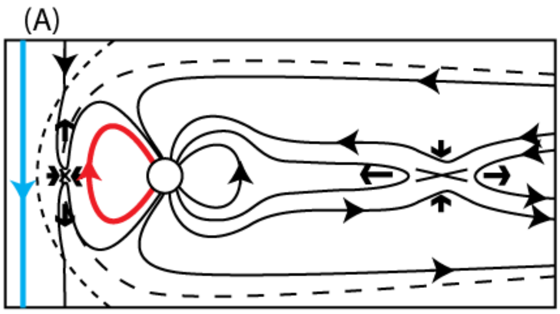
JANUARY 15, 1961

INTERPLANETARY MAGNETIC FIELD AND THE AURORAL ZONES

J. W. Dungey

Imperial College London

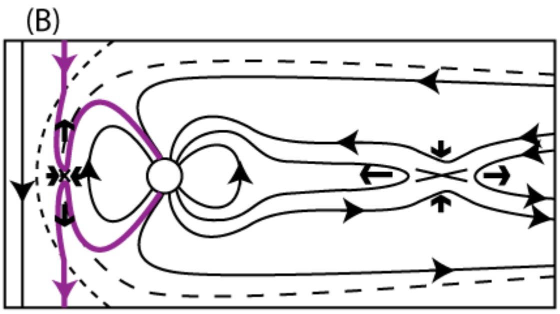
The open magnetosphere – the Dungey cycle



Eastwood et al., 2015

Imperial College London

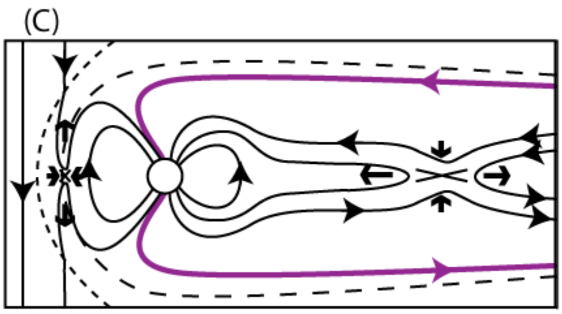
The open magnetosphere – the Dungey cycle



Eastwood et al., 2015

Imperial College London

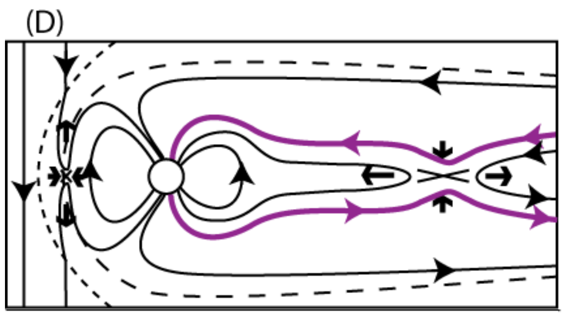
The open magnetosphere – the Dungey cycle



Eastwood et al., 2015

Imperial College London

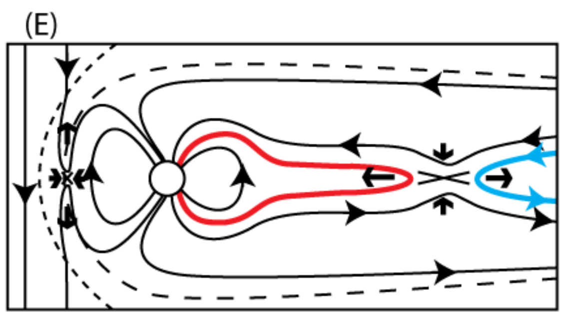
The open magnetosphere – the Dungey cycle



Eastwood et al., 2015

Imperial College London

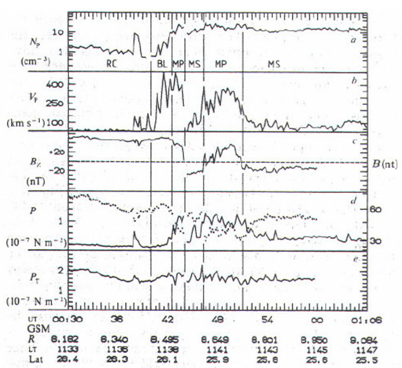
The open magnetosphere – the Dungey cycle

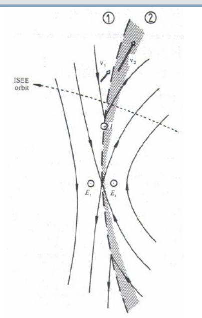


Eastwood et al., 2015

Imperial College London

Discovery of magnetopause reconnection jets

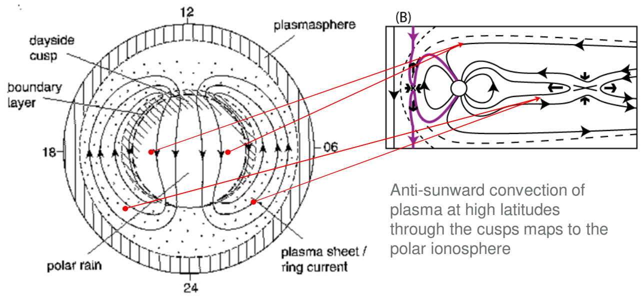




[Paschmann et al., 1979]

Imperial College London

Anti-sunward convection of plasma in the ionosphere

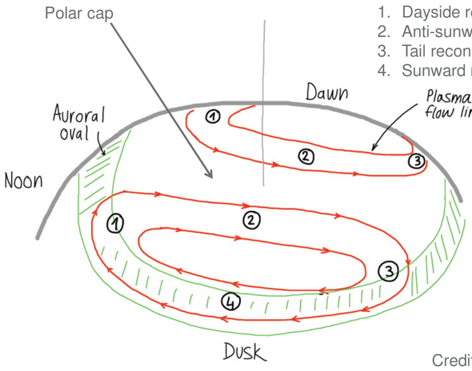


Anti-sunward convection of plasma at high latitudes through the cusps maps to the polar ionosphere

Imperial College London

Mapping into the ionosphere

1. Dayside reconnection
2. Anti-sunward convection
3. Tail reconnection
4. Sunward return flow near equator

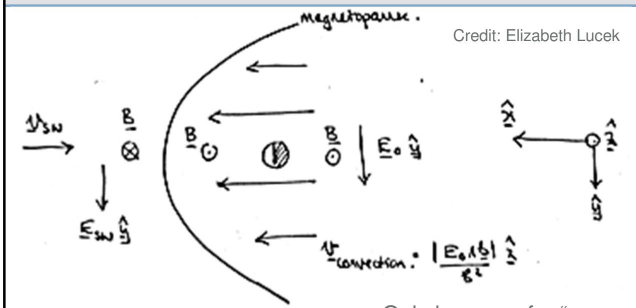


Credit: Ingo Mueller-Wodarg

Imperial College London

Convective flow in the equatorial plane

Credit: Elizabeth Lucek



$\mathbf{v}_{convection} = \frac{\mathbf{E}_0 \times \mathbf{B}}{B^2}$ in $+\hat{\mathbf{x}}$ direction

Only happens for "open magnetosphere" configuration (B_z<0)

Imperial College
London

Equatorial plasma convection

- Plasma convects in the equatorial plane sunward from the tail back to the dayside.

$$\boldsymbol{E}_0 = -\boldsymbol{v}_{conv} \times \boldsymbol{B}$$

- Points from dawn to dusk, i.e. in the +**y** direction
- Same as the orientation of the solar wind electric field if the IMF points southward
- Strength ~ 20% of the solar wind electric field
- It is sometimes said that the solar wind electric field penetrates into the magnetosphere.

Imperial College
London

Equatorial plasma corotation

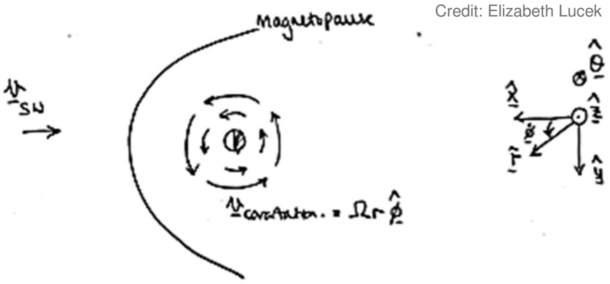
- The upper atmosphere co-rotates with Earth with angular velocity Ω_E.
- Plasma in the lower ionosphere is made to corotate through collisions with neutral atoms.
- The magnetic field is frozen into this ionospheric plasma
- Magnetospheric plasma on these field lines at higher altitude *also* co-rotates

$$v_{corot} = r\Omega_E\hat{\phi}$$

Imperial College
London

Corotational flow in the equatorial inner magnetosphere

Credit: Elizabeth Lucek



Imperial College London

Equatorial corotation electric field

Corotation electric field $\boldsymbol{E}_{corot} = -\boldsymbol{v}_{corot} \times \boldsymbol{B} = -\Omega_E r B \hat{\boldsymbol{r}}$

Magnetic field strength $B = B_E \left(\frac{R_E}{r}\right)^3$

Corotation electric field falls off as $1/r^2$ $\boldsymbol{E}_{corot} = -\Omega_E B_E R_E \left(\frac{R_E}{r}\right)^2 \hat{\boldsymbol{r}}$

Imperial College London

Corotation and convection

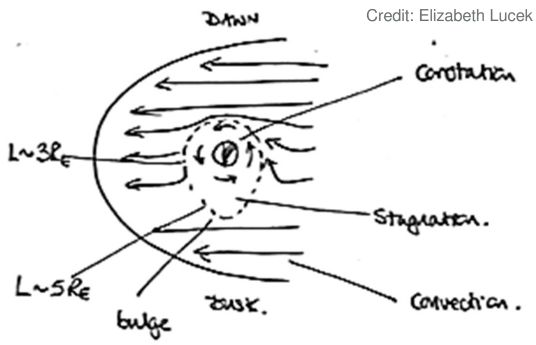
- Co-rotation and convection flows must interact
- Stagnation point on the dusk side where the corotation and convection electric fields cancel
- At some distance R' from the planet $\Omega_E R' B = E_0$
- Find a radius for the plasmapause, which marks the boundary between the region where corotation dominates, and the region where convection dominates.

$$R' = \sqrt{\frac{\Omega_E B_E R_E^3}{E_0}}$$

Imperial College London

Corotation and convection

Credit: Elizabeth Lucek



Imperial College London

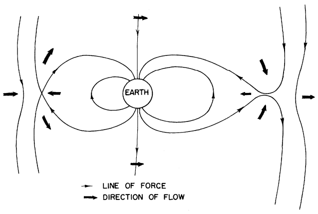
Northward IMF

- In reality, IMF can assume any orientation
  - Furthermore, magnetopause is not flat
  - Even if IMF is anti-parallel at one location, not necessarily the case over the whole magnetopause
- Northward IMF
  - Parallel to the Earth's magnetic field at the subsolar magnetopause,
  - IMF is then anti-parallel on the anti-sunward side of the cusp
  - Cusp reconnection can then occur
  - Dual-lobe reconnection could also occur

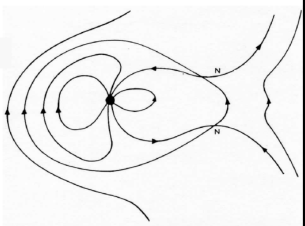
Imperial College London

Magnetic reconnection depends on IMF orientation

Southward IMF



Northward IMF



Dungey 1961, 1963

Imperial College London

Poleward of cusp reconnection – northward IMF

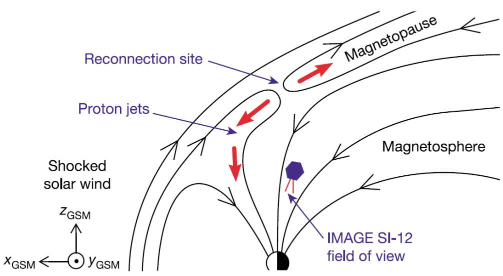


Image credit: Frey et al., 2003

Imperial College
London

Dual lobe reconnection

If poleward of cusp reconnection occurs in both hemispheres simultaneously, can add solar wind plasma directly to dayside magnetosphere

Enhance low latitude boundary layer

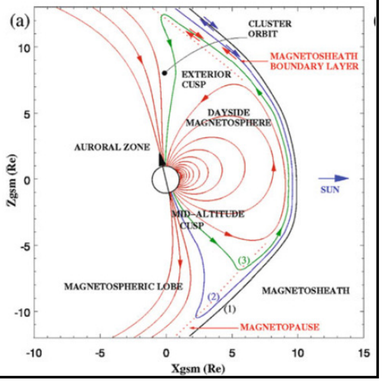


Image credit: Lavraud et al., 2004

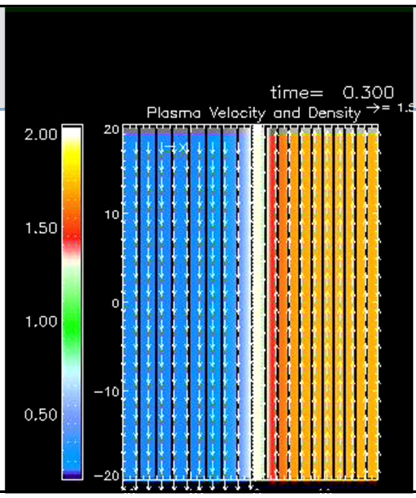
Imperial College
London

Kelvin-Helmholtz instability

- Fast magnetosheath flow on flank magnetopause = large velocity shear
- Susceptible to the Kelvin-Helmholtz Instability
  - “Wind over water”: generates waves which steepen into vortices and “break”
- Kelvin-Helmholtz Instability in plasmas
  - Stabilised if magnetic field is parallel to the flow
  - Most important for northward IMF (has been observed for southward IMF)
  - In nonlinear stage microscale instabilities or reconnection can occur
  - Enables plasma transport across the boundary
- KHI allows solar wind plasma to enter on the flanks during northward IMF

https://www.facebook.com/photo.php?v=10203103142636822&stream_ref=10

Imperial College
London



Simulation credit:
K. Nykyri

Imperial College
London

Kelvin-Helmholtz instability (northward IMF)

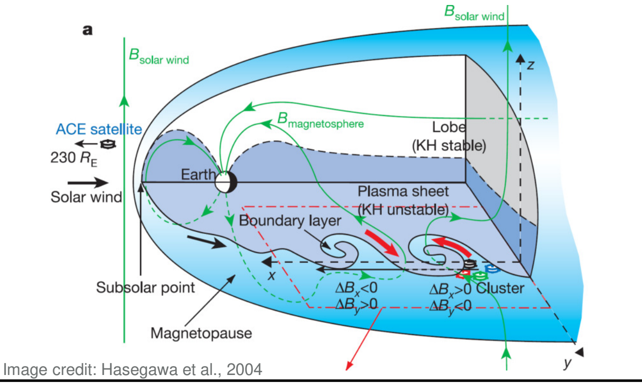
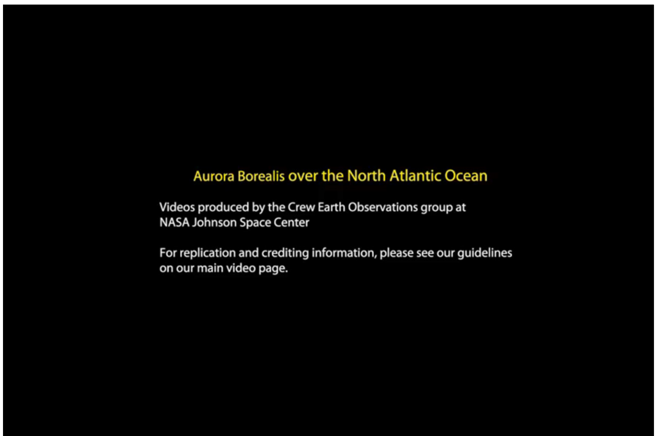


Image credit: Hasegawa et al., 2004

Imperial College
London

4. Aurora, substorms and storms

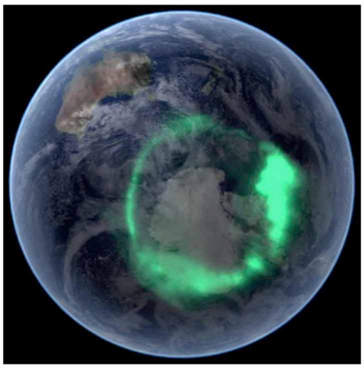
1. Aurora
   1. Properties
   2. Auroral substorm
2. Geomagnetic substorms
   1. Phases
   2. Connection to auroral observations
   3. Geomagnetic indices: the AE index
3. Geomagnetic storms
   1. Dst index



https://eol.jsc.nasa.gov/BeyondThePhotography/CrewEarthObservationsVideos/Aurora.htm

Imperial College London

The auroral oval



Credit: NASA

Imperial College London

Basic properties of the aurora

- Emission generated by energetic ions and e^- hitting upper atmosphere
- Nightside source – plasma sheet
  - Electrons with energies 1 – 15 keV precipitate down field lines from the magnetotail plasma sheet.
- Dayside source – polar cusp region
  - Magnetosheath ions can access atmosphere on dayside through the cusp leading to a small spot of dayside aurora ("proton aurora" not seen in visible light since on dayside)

We will mainly focus on the electron aurora here

Imperial College London

Basic properties of the aurora

- Can be seen from the ground with the naked eye at latitudes of around 70° in a belt called the aurora oval
- Intense aurora has an emission rate of ~10^6 Rayleigh (1 R = 10^6 photons/cm^{2}s)
- Appears in distinct arcs running east - west
- But also as a diffuse glow
- Emission height ~ 100-200km

Imperial College London

Colours of the aurora

- The colour depends on the neutral atom/molecule
- Energetic electron strikes a neutral atmospheric particle, causing ionisation/excitation. Photons emitted as atom returns to ground state
- **Auroral green line**: Atomic oxygen at 557.7 nm
- **Auroral red line**: Atomic oxygen at 630.0 nm
  - Excited energy states are metastable and long-lived, so need to avoid collisions to allow radiation. (Red ~ 2 minutes, green ~ 0.75 s)
  - Hence red at high altitude, green at lower altitude, and emission cut off once collisions quench emission process (nb red barely visible to the eye)
- Other emission
  - **Violet and blue** aurora: Molecular nitrogen at 391.4 nm, 427.0 nm, 470.0 nm
    - Can sometimes see a purple edge at the bottom of intense aurora
  - **Ultraviolet** aurora: Molecular nitrogen & atomic oxygen
  - **Infrared** aurora: Molecular oxygen

Imperial College London

http://spaceweathergallery.com/aurora_gallery.html

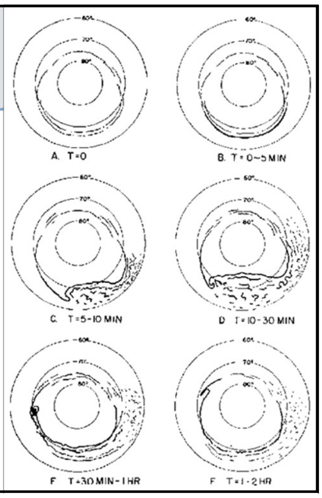
Multi-coloured aurora

Imperial College London

Auroral activity

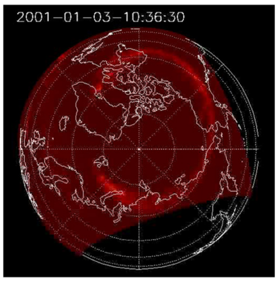
- Shun-ichi Akasofu first introduced the concept of the **auroral substorm**
  - Duration ~ 1-2 hours
- A: Quiet auroral arcs (drifting equatorwards, polar cap size increasing)
- B: Equatorward arc intensifies
- C: **Break up/Onset** Very bright structured aurora appear in the midnight sector
- D: **Expansion** of bright complex aurora westwards and polewards
- E/F: **Recovery** phase

Postulated on the basis of multiple ground based observations over the globe



Imperial College London

Auroral substorm seen from space



Credit: NASA

- UV auroral emission caused by precipitating electrons (IMAGE s/c)
- Sun is to the left
- Looking down on the north pole
- There are 2 auroral substorms in ~ 5 hours – typical occurrence rate
- Follows the basic qualitative pattern of the Akasofu picture

Imperial College London

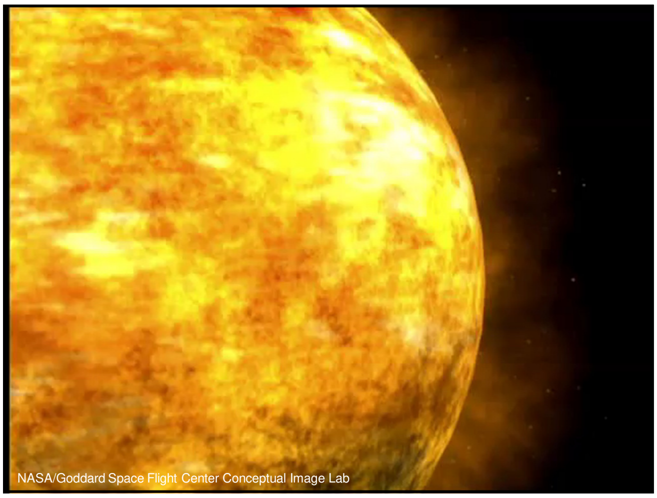
What is happening in the magnetosphere?

- Auroral substorms are associated with intervals of southward IMF
- Intervals of southward IMF occur naturally in the solar wind, and so substorms occur on a daily basis
- Physically, magnetic reconnection at the dayside magnetopause is enhanced if there is
  - a strong southward IMF component,
  - supplemented by fast solar wind,
  - for an extended period of time.
- What is the magnetospheric counterpart of the auroral substorm?

Imperial College
London

Geomagnetic substorms

- Dungey cycle does not capture the fact that the magnetosphere can be highly dynamic.
- Continued dayside reconnection under southward IMF leads to
  - An accumulation of open flux in the magnetotail,
  - Storage of energy in the lobe magnetic field.
- This accumulated energy undergoes periodic release in what is known as a magnetospheric substorm.
  - Magnetotail reconnection
  - Evolution of current systems linking magnetosphere and ionosphere
  - Dynamic nightside aurora



NASA/Goddard Space Flight Center Conceptual Image Lab

Imperial College
London

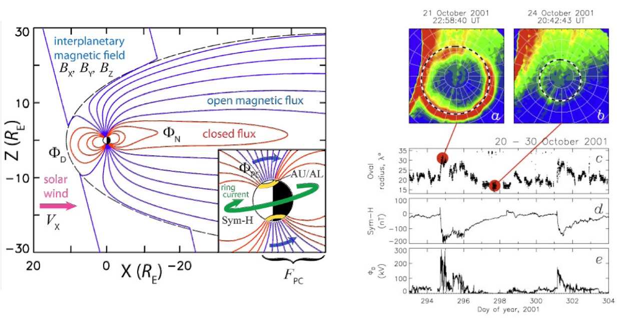
Phases of the substorm cycle: 1. Growth

- B_{IMF} turns Southward
  - Leads to dayside reconnection
  - Flux carried tailwards over pole via Dungey cycle
- More open flux:
  - "Polar cap" (region of open flux connected to ionosphere) increases
  - More flux in tail, fields lines stretched out – less dipolar
- Energy in magnetotail lobes increases
  - Cross tail current density in magnetotail neutral sheet increased
  - Current sheet thinning in tail

Imperial College London

Image: Steve Milan (Leicester)

Monitoring magnetotail loading and unloading

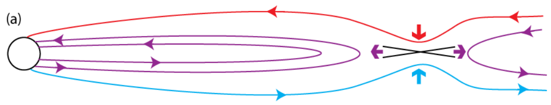


Milan, GRL, 2009

Imperial College London

Eastwood et al., 2015

Phases of the substorm cycle: 1. Growth



- The distant X-line is formed in response to magnetospheric convection like in the Dungey cycle (~100 Re downtail)
- This is not sufficient to prevent the open flux in the magnetotail lobes from increasing

Imperial College London

Phases of the substorm cycle: 2. Onset

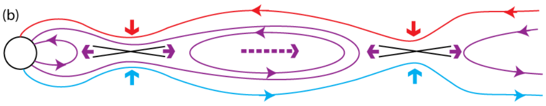
- Fast reconnection in tail over a range of longitudes
  - Releases magnetic energy
  - Fast plasma flow towards Earth
- Reduced current in tail, much connects into ionosphere
  - Field-aligned current (particle flow/precipitation into ionosphere)
  - Substorm current wedge
- Enhanced aurora (mostly fast e^-)
  - Precise nature of acceleration processes still not very well understood
  - Impact of many particles in ionosphere increases ionisation, hence conductivity: current concentrated in ring in latitude: “auroral electrojet”
  - **B** signature of current in ground-based magnetometers
- Injects energetic particles into inner magnetosphere: ring current and radiation belts.

Imperial College London

Eastwood et al., 2015

Phases of the substorm cycle: 2. Onset

(b)



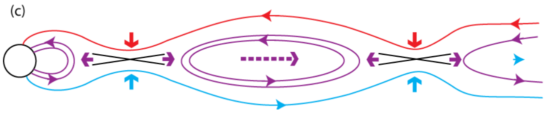
- Formation of a *Near Earth Neutral Line*
- Reconnection on closed field lines (purple)
- Closed loop of field formed in this idealised cartoon – a *plasmoid*
- Bounded by magnetic tension of closed field enveloping it

Imperial College London

Eastwood et al., 2015

Phases of the substorm cycle: 3. Plasmoid release

(c)



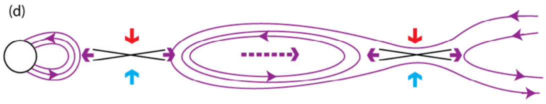
- NENL proceeds to reconnect open field lines
- Plasmoid is released
- This corresponds to the *expansion phase* in the aurora

Imperial College London

Eastwood et al., 2015

Phases of the substorm cycle: 3. Plasmoid release

(d)



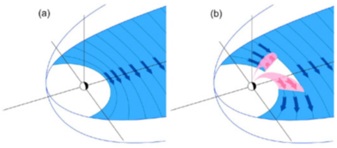
- Plasmoid moves downtail
  - In reality, if the reconnecting fields are not perfectly anti-parallel, then the plasmoid will in fact be a flux rope.
- Formation of the NENL thus results in
  - Earthward injection of plasma
  - Bright auroral displays (auroral substorm)
  - Associated disturbances to ground based magnetometers

Imperial College London

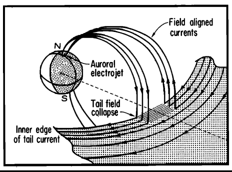
Electrodynamic coupling

- NENL is of finite extent across tail
- Field lines Earthward of the NENL are more curved
- If field lines are more curved, the cross tail current is less in the middle of the tail.
- Current is diverted along field lines into the ionosphere/aurora
- Substorm current wedge
- Auroral electrojet

[Ganuskina et al., 2018]



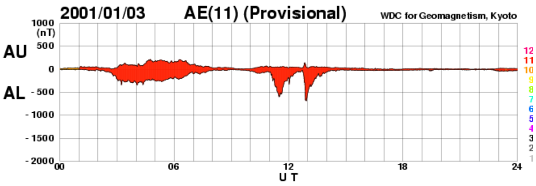
[McPherron, 1973]



Imperial College London

http://wdc.kugi.kyoto-u.ac.jp/ae_provisional/index.html

Magnetic signature of the aurora



Magnetic signature & strength of substorm characterised by AE index

12 magnetometers at different longitudes in the northern auroral latitudes
Each measures deviations in field (mainly due to the auroral electrojet current)
AL = most negative deviation
AU = most positive deviation
AE = AU-AL

Imperial College London

Phases of the substorm cycle: 4. Recovery

- Near earth and magnetosphere return to pre-substorm configuration
- Auroral oval contracts
- Auroral luminosity weakens
- Plasmasheet gradually thickens again
- Plasmoid travels into far tail

Whilst basic picture is reasonably well understood, there are still many things we don't understand!
In particular, precise details of substorm timing, and how things map between the magnetosphere and the aurora

Imperial College
London

Geomagnetic storms

- Substorms are the consequence of dayside reconnection
  - `southward' IMF conditions
- Strength of solar wind coupling
  - Described by rate at which plasma circulates through the magnetosphere
  - Convection electric field
  - Ultimately depends on the IMF orientation and the solar wind speed.
- If the southward magnetic field points strongly southward, and the solar wind is fast, then the solar wind will strongly drive magnetospheric convection.
- If these conditions persist, then a geomagnetic storm may develop
- Injection of plasma into inner magnetosphere – strong ring current and radiation belt enhancements, multiple substorm events, dynamic aurora

Imperial College
London

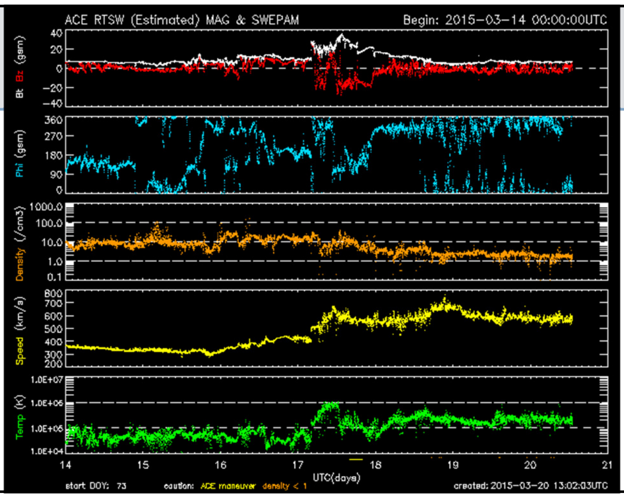
Drivers of geomagnetic storms

Coronal Mass Ejections

- Move at high speeds through the heliosphere
- Can contain long intervals of southward IMF (in the flux rope core)
- *Largest geomagnetic disturbances are associated with CMEs*
- More frequent during solar maximum and declining phase

Corotating Interaction Regions

- Solar minimum: dipole is tilted with respect to the rotation axis
- Fast solar wind runs into slow solar forming the CIR
- Trailing high speed solar wind contains large-amplitude Alfvén waves, which can have long duration intervals of southward IMF
- significant source of geomagnetic storms (tend to be weaker CME generated storms)



Imperial College London

Characterising geomagnetic storms – the Dst index

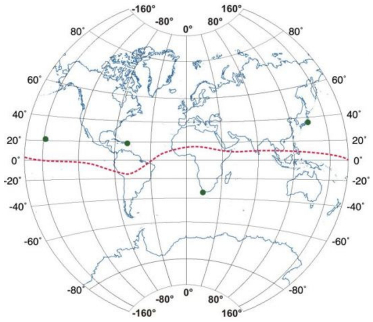
Four stations at equatorial latitudes

Find average deviation in the Earth's magnetic field

Storm time ring current points east to west,

Thus it reduces the equatorial magnetic field on the ground

If reduced by more than 100 nT, considered a strong storm

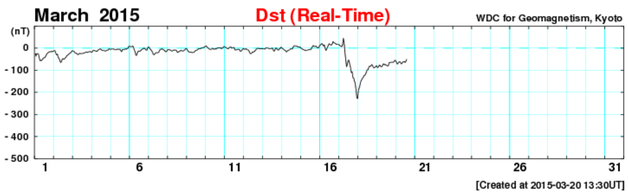


http://roma2.rm.ingv.it/en/themes/23/geomagnetic_indices/27/dst_index

Imperial College London

http://wdc.kugi.kyoto-u.ac.jp/dst_realtime/presentmonth/index.html

Geomagnetic storms



Initial phase (minutes)
- Dst increases to positive values because dayside magnetopause is compressed by the arrival of the CME

Main phase (hours)
- Dst decreases to several hundred nT negative as the strength of the ring current increases

Recovery phase (hours – days)
- ring current ions are gradually lost and magnetic perturbation decreases

Imperial College London

Today's lecture: the magnetosphere

1. Basic properties of the magnetosphere
2. The structure of the magnetosphere
3. Magnetospheric dynamics
4. Aurora, substorms and storms