The Physics of Space Plasmas

Why Space Physics?
A Brief Overview

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BOSTON COLLEGE ISR INSTITUTE FOR SCIENTIFIC RESEARCH

Why Space Physics?

Personal background:

- My colleagues Susan Gussenhoven, half-jokingly would often refer to physics "the last of the dogmatic sciences." Her critique had the ring of truth. During my years as a student at BC and MIT physics was offered in standard textbooks as a set of eternal laws to be applied in solving homework problems.

- Only MIT Professor Uno Ingaard, who taught classical mechanics and plasma theory, insisted we write term papers on the historical roots of quantum theory in Hamiltonian mechanics, and J. J. Thompson's "plum pudding" model of atoms as small blobs of plasma.

- One MIT professor told us that making up a test for physics graduate students is impossible. It's either so hard everyone fails or so easy everyone gets an A. Ingaard's term paper seems a useful alternative. By next week please vote on whether you prefer to write a final examination or a term paper.

- About 10 years ago Alv Egeland asked me to help write scientific biographies of Kristian Birkeland and Carl Størmer. The experience opened my eyes to seeing our science in a very different, evolutionary light that I will try to convey to you as a historical enterprise and from perspectives gained during my years of research in the field.

Why Space Physics?

<u>Tentative Course Outline:</u>

Lecture 1:	**Historical Development: Aristotle to Sputnik**
Lecture 2:	**Early Discoveries in Space Program**
Lecture 3:	**Tools of the Trade: Sensors for all occasions**
Lecture 4:	**High-Latitude Phenomenology and Sources**
Lecture 5:	**Conservation of Mass, Momentum and Energy**
Lecture 6:	**Electrostatic Wave-Particle Interactions**
Lecture 7:	**Electromagnetic Wave-Particle Interactions**
Lecture 8:	**Experimental Evidence for Magnetic Merging**
Lecture 9:	**Magnetic Substorms**
Lecture 10:	**Magnetic Storms**
Lecture 11:	**Solar Sources of Geomagnetic Storms**
Lecture 12:	**Dynamics of the Equatorial Ionosphere**
Lecture 13:	**Radiation Belt Remediation**
Lecture 14:	**Satellite Drag Problems**
Lecture 15:	***Verbindung***

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Historical Background:

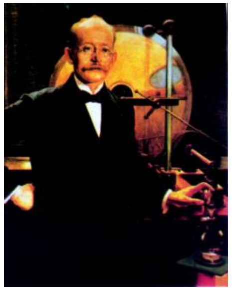
- c. 350 BC: **Aristotle** in his *Meteorology* refers to auroral lights as $\chi\alpha\sigma\mu\alpha\tau\alpha$
- c. 37 AD: **Tiberius** sent a Roman legion to assist burning city
- 1600 **William Gilbert:** *de Magnete :* "The Earth is a giant magnet."
- 1621 **Pierre Gassendi:** introduced term "aurora borealis" = "northern dawn"
- 1691 - 1702 **Edmond Halley:** Hollow Earth, with two magnetic sources: explored magnetic field in north and south Atlantic.

  1716 - Noted connection between magnetic disturbances and aurorae
- 1724 **Capt. James Cook:** reported seeing the "aurora australis"
- 1724 **George Graham:** identifies Sq current system
- 1741 **Ander Celsius and Olaf Peter Hiorter:** magnetic needles fluctuated whenever aurorae were above Uppsala.
- 1748 **George Graham:** demonstrated long term migration of magnetic poles
- 1820 **Hans Christian Oersted:** electric currents create magnetic effects.

  André-Marie Ampère: magnetism is force between electric currents.
- 1825 **Christofer Hansteen:** Magnetic expedition across Siberia
- 1831 **Michael Faraday:** time-varying currents induce voltage in coils.
- 1837 **Carl Friedrich Gauss:** Göttingen Magnetic Union deployed across Europe.

  1839 *Algemeine Theorie des Erdmagnetismus*: applies potential formalism: B_{int} vs B_{ext}
- 1843 **Samuel Schwabe** identified 11-year sunspot cycle.
- 1859 **Richard Carrington** saw white light solar flare → magnetic *storm* 17 hrs later
- 1865 **James Clerk Maxwell:** *A Dynamical Theory of the Electromagnetic Field*
- 1881 **Herman Fritz:** *Das Polarlicht:* most probable locations of aurorae
- 1895 **Wilhelm Röntgen:** discovered X-rays
- 1886 **Henri Becquerel:** identified natural radioactivity
- 1897 **John J. Thompson:** discovered electrons ==> plumb pudding model of atoms

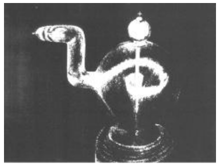
Why Space Physics?



<u>Kristian Birkeland</u> (1867 – 1917)

- **Brief history of Norway and Royal Frederik University, Kristiania**
- **Birkeland and Størmer encounters with Elling Bolt Holst (1849–1915)**
- **University: Chemistry math or physics? ➔ *Presetres* award**
- **1893 – 1894: Post graduate studies in Paris with Poincaré,**
  - **Research in Geneva, Bonn, Leipzig on properties of electric sparks and electromagnetic waves.**
  - **Published first general solution of Maxwell's equations;**

- **1895: Initiated cathode-ray studies in magnetic fields (Kristiania)**
- **1896: Earliest speculations on solar origins of auroral electrons**
- **1897: Disastrous first auroral expedition to Finnmark**



- **1898: *Verdens Gang*: "Sunspots and Northern Lights: A Message from the Sun"**
- **1898: Appointed Professor of Physics by Swedish King Oscar II**
- **1899 – 1903: Auroral Expeditions**
- **1903: Meeting with Carl Størmer**
- **1908, 1913: Publication of NAPE volumes I and II**

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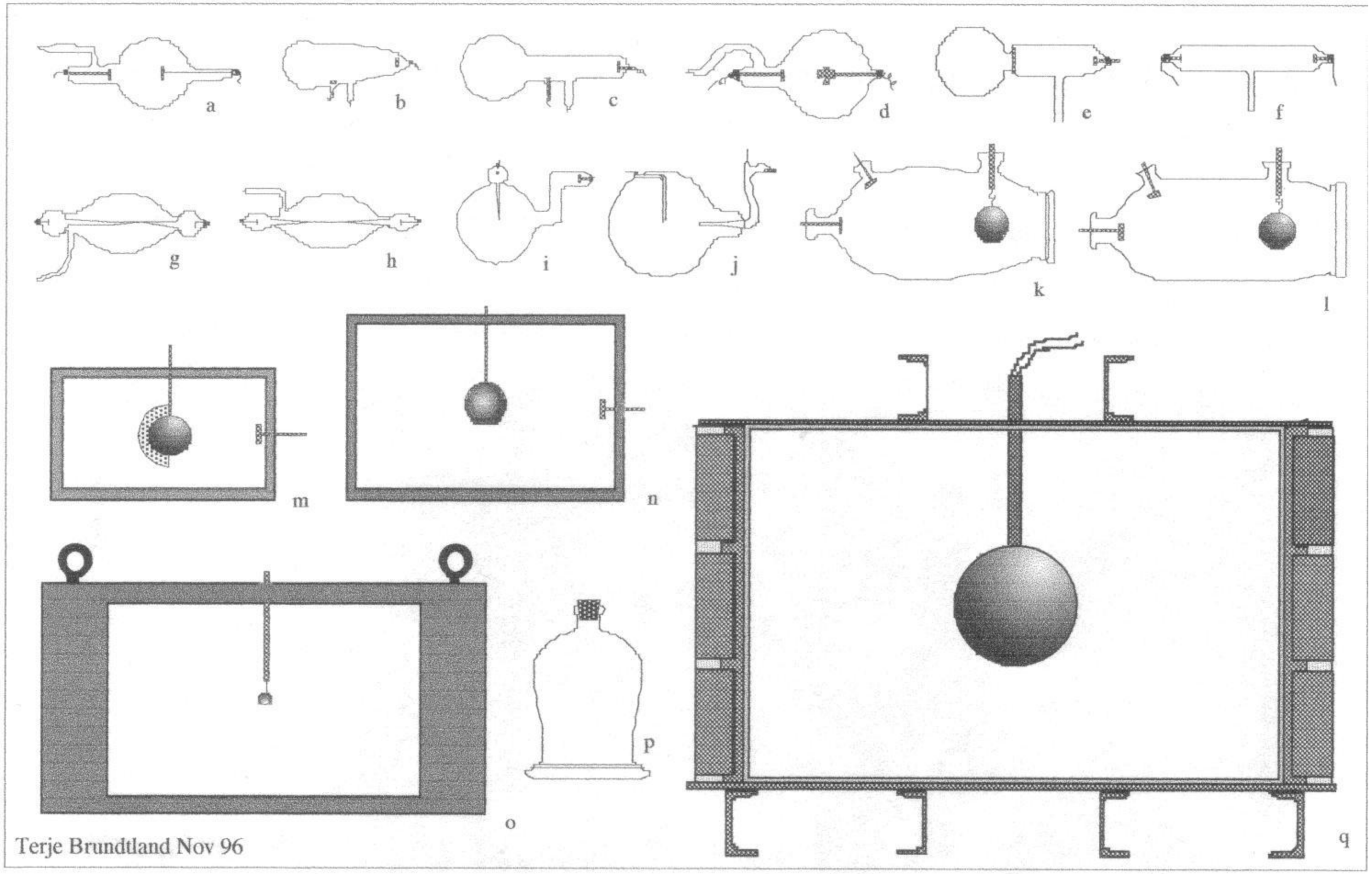
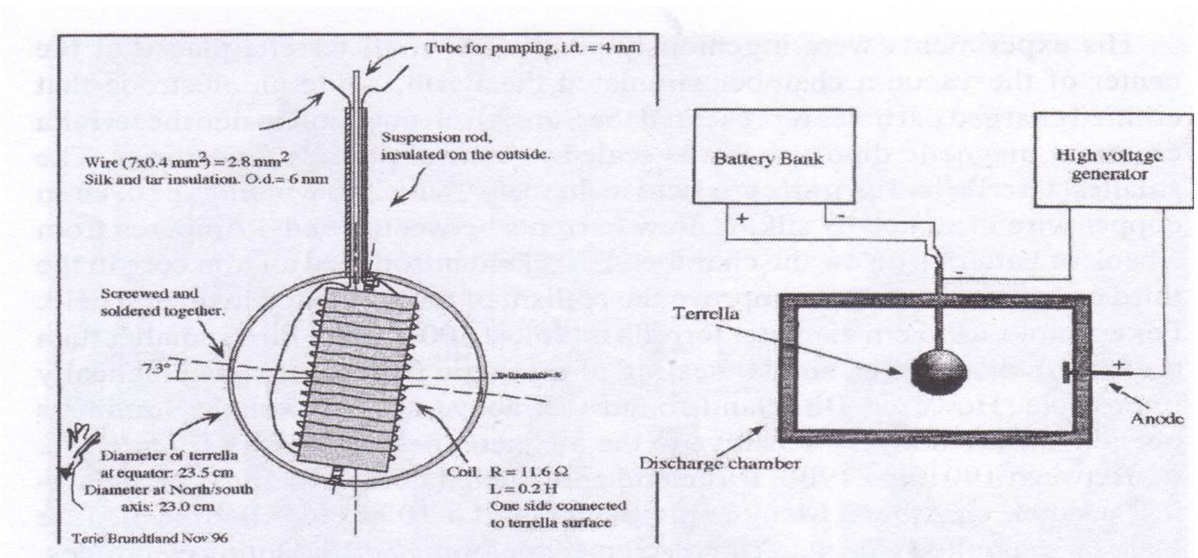
Birkeland's 16 different discharge tubes and vacuum chambers.



Why a Ring Current?



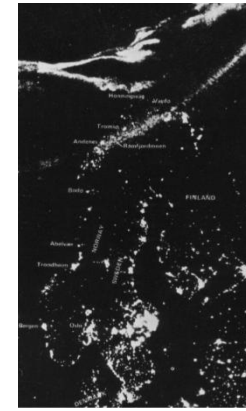
Schematic shows the principles underlying terrella experiments. They to illustrate how dipolar magnetic fields were produced in the terrella vacuum chamber and effects on incoming cathode rays.

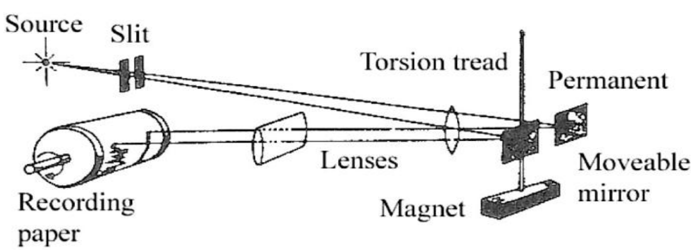
Why Space Physics?

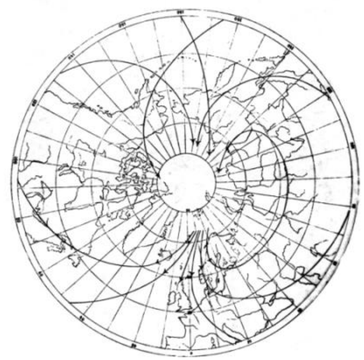
Kristian Birkeland

Polar expeditions to Finnmark

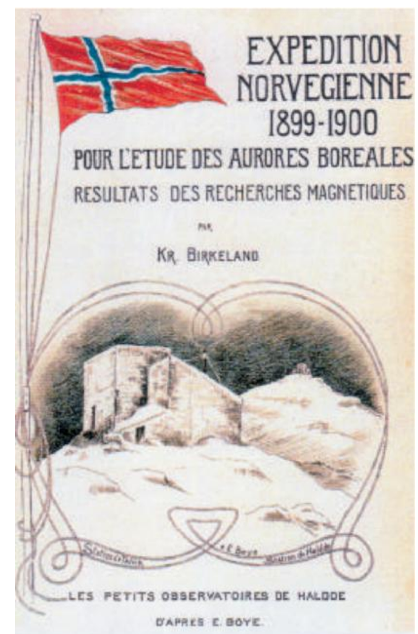
- 1897 Preliminary expedition ends quickly in disaster
- 1899-1900 First permanent observatories at Haldde & Talvik;
  - GLat ~ 70º; Mlat ~ 67º; Alt ~ 900 m; Separation 3.5 km
  - Auroral cameras with telephone connection for height determinations
  - Magnetometer to record disturbances







Auroral Current System



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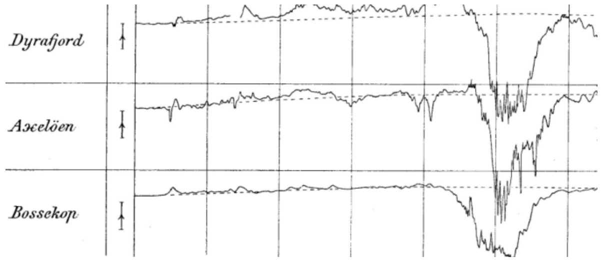
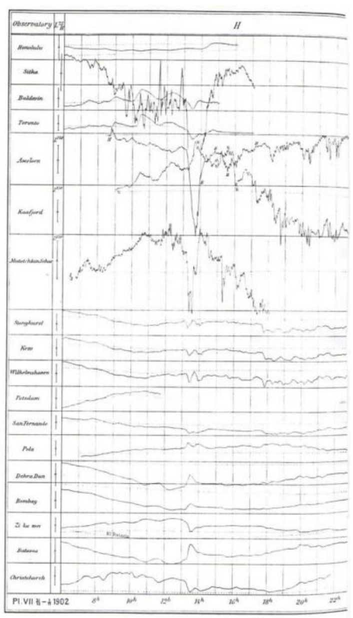
Why Space Physics?

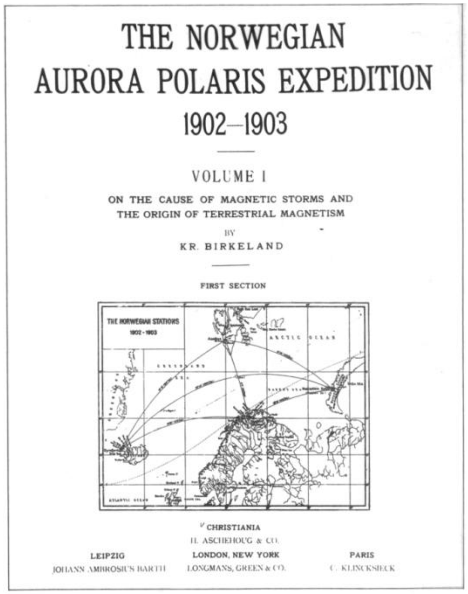
Kristian Birkeland

Polar Expedition 1902 - 1903



Polar elementary storms identified




THE NORWEGIAN
AURORA POLARIS EXPEDITION
1902—1903

VOLUME I
ON THE CAUSE OF MAGNETIC STORMS AND
THE ORIGIN OF TERRESTRIAL MAGNETISM
BY
KR. BIRKELAND

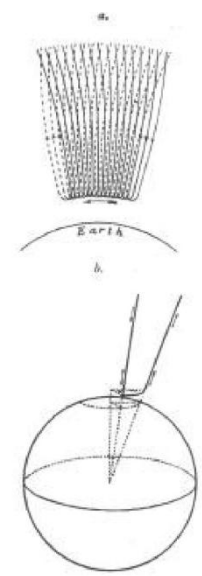
FIRST SECTION

CHRISTIANIA
H. ASCHEHOUG & CO.

LEIPZIG	LONDON, NEW YORK	PARIS
JOHANN AMBROSIUS BARTH	LONGMANS, GREEN & CO.	C. KLINCKSIECK

- Showed that during disturbances > 5 M-Amps flow in upper atmosphere.

- Postulates solar source connected to atmosphere via field-aligned currents



Chronology in Great Britain

- **Sir William Thomson, Lord Kelvin (1892): "It seems as if we may also be forced to conclude that the supposed connection between magnetic storms and sunspots is unreal, and that the seeming agreement between the periods has been mere coincidence."**

- **Gerald Francis Fitzgerald (1892): "Is it possible then that matter starting from the Sun with the explosive velocities we know possible there, and subject to an acceleration of several times the solar gravitation, could reach the Earth in a couple of days?"**

- **E. W. Maunder (1905), Magnetic disturbances, 1882 to 1903, as recorded at the Royal Observatory, and their association with sunspots, *Mon. Not. R. Astron. Soc.*, 65, 2.**

- **Arthur Schuster (1911), On the origin of magnetic storms, *Proc. Roy. Soc, London, 85*, 44-50.**

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Chronology in Great Britain

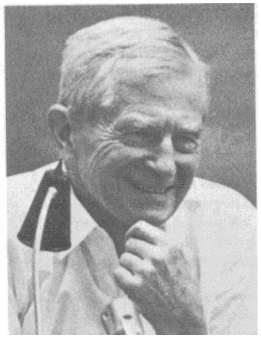
- **Sydney Chapman, (1913), On the diurnal variations of the earth's magnetism produced by the moon and sun, *Phil. Trans Roy. Soc., A 213*, 279-321.**

- **Sydney Chapman, (1918), An outline of a theory of magnetic storms, *Proc. Royal Soc. London, 95*, 61-83.**

- **Sydney Chapman and V. C. A. Ferraro, (1931), A new theory of mag-netic storms, Part I. The initial phase, *Terr. Magn. Atmos. Elect. 36*, 77.**

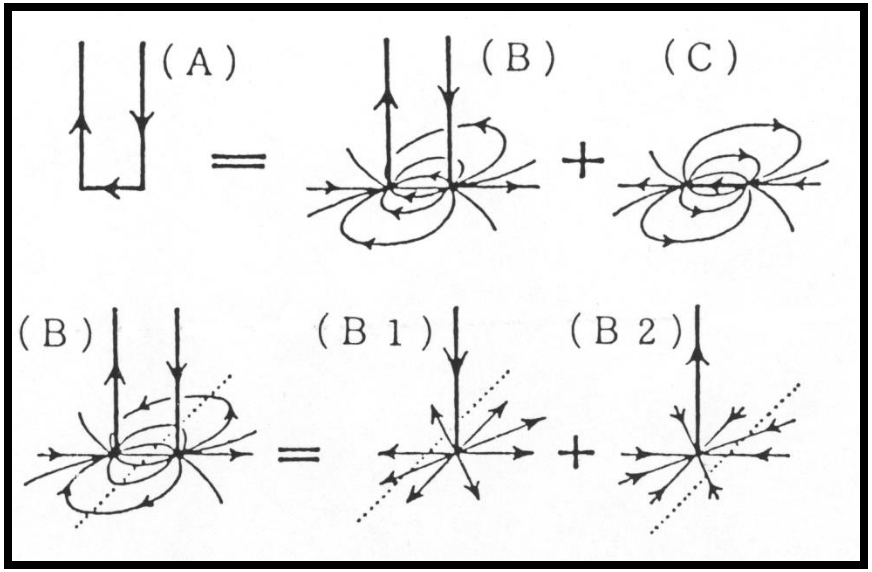
- **E. H. Vestine and Sydney Chapman (1938), The electric current-system of geomagnetic disturbances, *Terr. Magn. Atmos. Elect., 43*, 351-382.**

- **Sydney Chapman (1957), Notes on the solar corona and terrestrial ionosphere, *Smithsonian Contrib. Astrophys., 2*, 1.**



Sydney Chapman

FAC Controversy Resolved

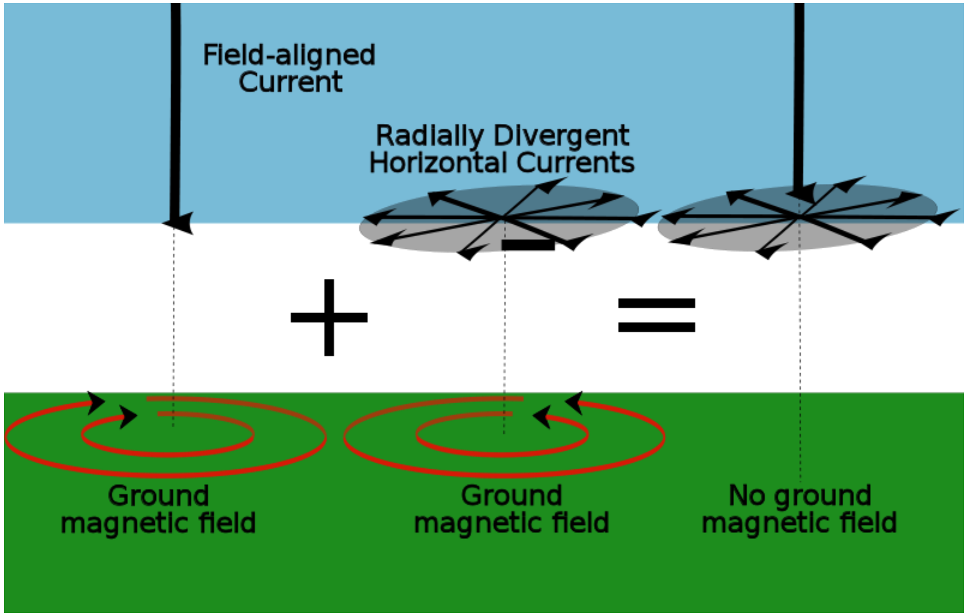


Hannes Alfvén

- *Fukushima* (1969): Equivalent current and FAC models predict same ground perturbations
- *Fukushima* (1989) finds error in *Vestine and Chapman* (1938)

Why Space Physics?

Fukushima's Theorem

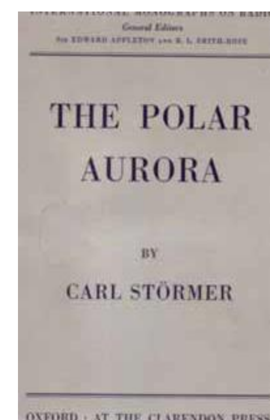


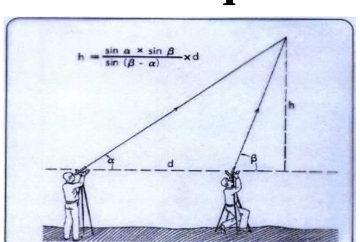
- ***Zmuda and Armstrong*: TRIAD's discovery of field-aligned currents.**

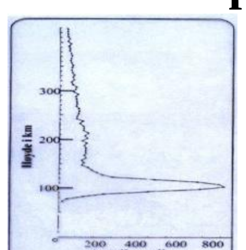
Why Space Physics?

<u>Carl Størmer</u> (1874 – 1957)

- Born in Skein ~ 250 km south of Norway: son of a pharmacist
- Moved to Kristiania at age of 12 to attend *Katedralskolen*
- University: 1892 - 1898 Botany, Mathematics or Geology?
- 1898 – 1902: Post-graduate studies in Paris with Poincaré, and Camille Jordan ➔ University of Gottingen
- 1890 – 1900: Covert photography with "Spion" camera
- 1903: Appointed Professor of Pure Mathematics at U. of Kristiania;
- 1903: Discusses auroral problem with Birkeland begins calculating
- 1909: Størmer-Krogness auroral camera
- 1910: Postulates need for the ring current
- 1910 – 1913: Auroral Campaigns in Bossekop in Finnmark
- 1914: Establishes Norwegian auroral network
- 1927: Explains cosmic rays
- 1930: Publishes first of several *Auroral Atlases* for IUGG
- 1955: At request of Appleton writes/published *The Polar Aurora*







Why Space Physics?

The force exerted by a time stationary magnetic field B on a particle with mass m, charge q and moving at a velocity is,

(1)
$$m\frac{d\vec{v}}{dt} == m\frac{d^2\vec{x}}{dt^2} = q[\vec{v}\times\vec{B}(\vec{x})]$$

B is exerted perpendicular to a charged particle's velocity its speed v, thus momentum p = mv and kinetic energies E_k = ½ mv^2 are constants of the motion.

Størmer approximated B as a centered dipolar whose axis points along the Earth's axis of rotation. In spherical coordinates the magnetic field and trajectory equations are

(2)
$$\vec{B}(\vec{x}) = \vec{B}(r,\theta) = -\frac{M}{r^3}\left(2Cos\theta\hat{r} + Sin\theta\hat{\theta}\right) = B_r\hat{r} + B_\theta\hat{\theta}$$

$$(ds)^2 = (dr)^2 + (rd\theta)^2 + (rSin\theta d\phi)^2$$

(3)
$$\left(\frac{dr}{ds}\right)^2 + \left(r\frac{d\theta}{ds}\right)^2 = 1 - \left(rSin\theta\frac{d\phi}{ds}\right)^2$$

Why Space Physics?

Størmer argued this equation is analogous to the motion of a particle moving in a potential well. Terms on the left side of the equation are like kinetic energy; $\left(rSin\theta\frac{d\phi}{ds}\right)^2$ acts like a potential energy barrier.

Transforming to the spatial domain, $\frac{d}{dt}\rightarrow\frac{ds}{dt}\frac{d}{ds}=v\frac{d}{ds}$ the force balance equation becomes

(4)
$$\frac{d^2\vec{x}}{ds^2}=\frac{q}{mv}\left[\frac{d\vec{x}}{ds}\times\vec{B}(\vec{x})\right]=\frac{q}{p}\left[\frac{d\vec{x}}{ds}\times\vec{B}(\vec{x})\right]$$

Consider the scalar product of this equation with the quantity $\hat{e}_3\times\vec{x}=rSin\theta\hat{e}_\phi$

(5)
$$\frac{d^2\vec{x}}{ds^2}\cdot(\hat{e}_3\times\vec{x})=\frac{d}{ds}\left(r^2Sin^2\theta\frac{d\phi}{ds}\right)$$

(6)
$$\frac{q}{p}\left(\frac{d\vec{x}}{ds}\times\vec{B}(\vec{x})\right)\cdot(\hat{e}_3\times\vec{x})=\frac{q}{p}\left(\frac{d\vec{x}}{ds}\times\vec{B}(\vec{x})\right)_\phi rSin\theta=\frac{q}{p}\left(\frac{dr}{ds}B_\theta-r\frac{d\theta}{ds}B_r\right)rSin\theta$$

Applying the $\nabla\cdot\vec{B}=\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2B_r\right)+\frac{1}{rSin\theta}\frac{\partial}{\partial\theta}\left(Sin\theta B_\theta\right)=0$ **condition yields**

(7)
$$\frac{q}{p}\left(\frac{dr}{ds}B_\theta-r\frac{d\theta}{ds}B_r\right)rSin\theta=\frac{q}{p}\cdot\frac{d[\Phi(r,\theta)/2]}{ds}$$

Why Space Physics?

(8) $$\frac{\Phi(r,\theta)}{2\pi} = r^2 \int_0^\theta Sin\theta' B_r(r,\theta') d\theta'$$

is the magnetic flux between the pole and colatitude θ.

Combining equations (7) and (5), (4) can be written as a perfect derivative

$$\frac{d}{ds}\left[\frac{q}{p}\left(r^2 Sin^2\theta \frac{d\phi}{ds}\right) - \frac{\Phi(r,\theta)}{2\pi}\right] = 0$$

The quantity in brackets must be a constant C along trajectories and

(9) $$rSin\theta \frac{d\phi}{ds} = \frac{q}{p}\left[\frac{C - \Phi(r,\theta)/2\pi}{rSin\theta}\right]$$

(10) $$\left(\frac{dr}{ds}\right)^2 + \left(r\frac{d\theta}{ds}\right)^2 = 1 - \left(\frac{q}{p}\right)^2 \cdot \left(\frac{C - \Phi(r,\theta)/2\pi}{rSin\theta}\right)^2$$

For a magnetic dipole (9) becomes

$$\frac{\Phi(r,\theta)}{2\pi} = r^2 \int_0^\theta Sin\theta' B_r(r,\theta') d\theta' = -\frac{M}{r}\int_0^\theta 2Sin\theta' Cos\theta' d\theta' = \frac{M \cdot Sin^2\theta}{r}$$

Why Space Physics?

$rSin\theta\frac{d\phi}{ds}$ **has a geometric interpretation as the component of** $\frac{d\vec{x}}{ds}$ **perpendicular to the magnetic meridional plane and is equal to the Sin of angle χ between the meridional plane and the trajectory at its intercept**

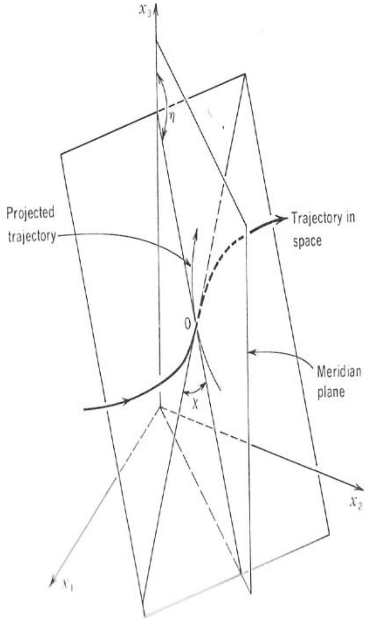
(11) $$Sin\chi = rSin\theta\frac{d\phi}{ds} = \left(\frac{q}{p}\right)\cdot\left(\frac{M\cdot Sin\theta}{r^2} + \frac{C}{rSin\theta}\right)$$

This can be simplified by defining a distance $r_S = \sqrt{qM/p}$

(12) $$Sin\chi = \left(\frac{r}{r_S}\right)^2 Sin\theta + \left(\frac{r}{r_S}\right)\cdot\frac{2\gamma}{Sin\theta}$$

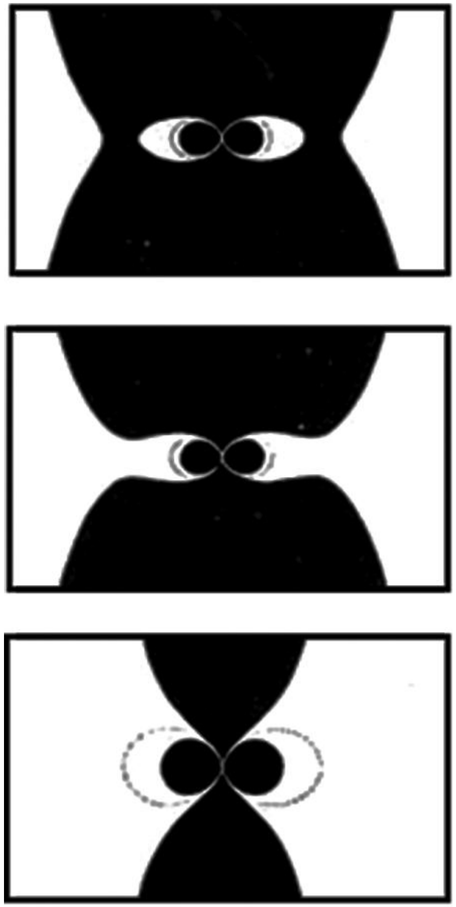
γ = ($C\, r_S$ / 2 M)

(13) $$\left(\frac{dr}{ds}\right)^2 + \left(r\frac{d\theta}{ds}\right)^2 = 1 - \left(\frac{q}{p}\right)^2\left[\frac{C - \frac{1}{2\pi}\Phi}{rSin\theta}\right]^2$$



Which has real solutions only if $\left(\frac{q}{p}\right)^2\left[\frac{C - \frac{1}{2\pi}\Phi}{rSin\theta}\right]^2 \le 1$

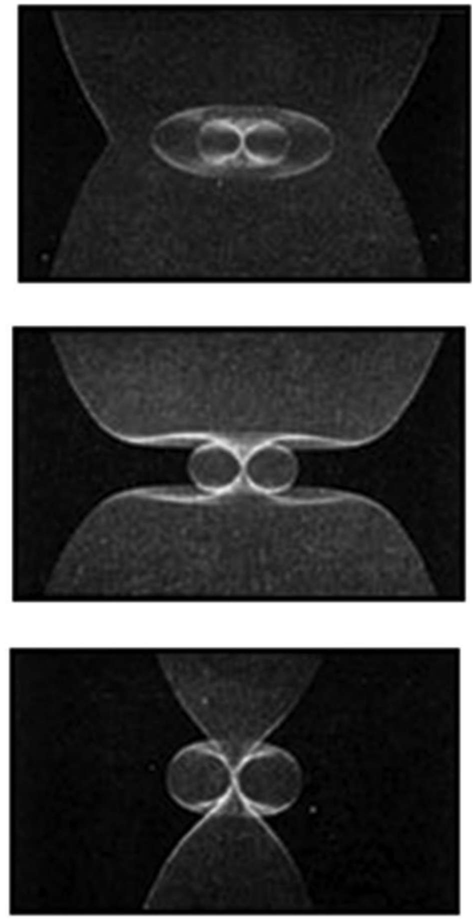
Why Space Physics?

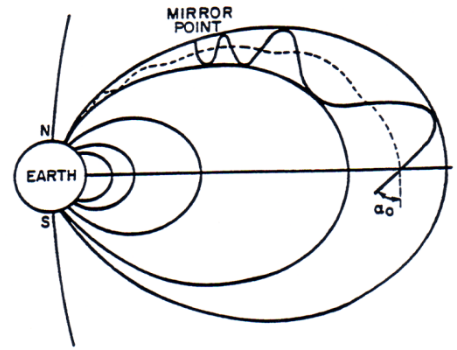


$\gamma = -1.016$

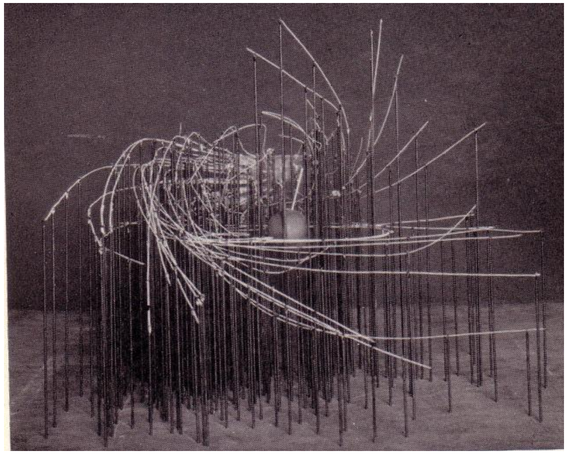
$\gamma = -0.97$

$\gamma = -0.5$





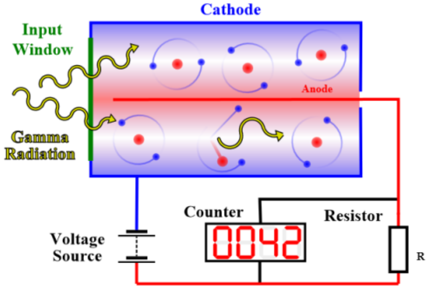
Predicted trapped orbits



Størmer's forbidden and allowed regions

Why Space Physics?

Cosmic Rays:



- In the 1880s it was known that sealed electrometers slowly discharge indicating the presence of ionization in the chamber.

- 1896 Becquerel's discovery of natural radio activity provided a natural mechanism for ionization. Earth-source explanation.

- 1909 Theodore Wulf : electrometers discharge more quickly at the top of the Eiffel tower than at its base.

- 1912 Victor Hess: balloon experiment shows 3 times higher ionization rate at 5500 m than at ground. ➔ γ-rays from space explanation.

- 1927 Jacob Clay: Showed that radiation increased with latitude.

- 1927 Carl Størmer: "I know why!"

Why Space Physics?

<u>The Ring Current:</u>

- **Fritz showed that the most probable location to see aurora is at magnetic colatitude**

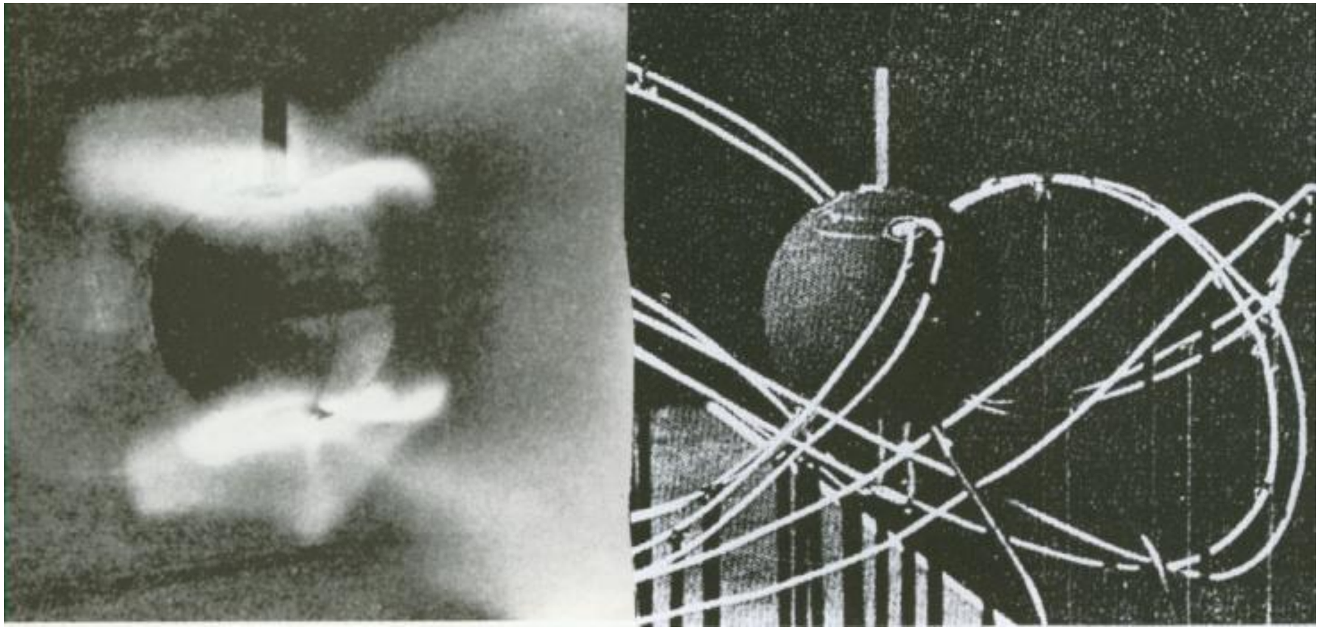
- **Størmer's calculations and Birkeland's terrella experiments placed it near 23° MCoLat . However, he observed aurora over Oslo ~600 times.**

- **Eventually he concluded that during storms his magnetic field model was in error.**

- **In 1910 he postulated the existence of a ring of current that grows around the Earth during magnetic disturbances.**

- **His calculations showed that if the ring current produced a 300 nT perturbation on the ground the aurora should indeed appear over Oslo.**

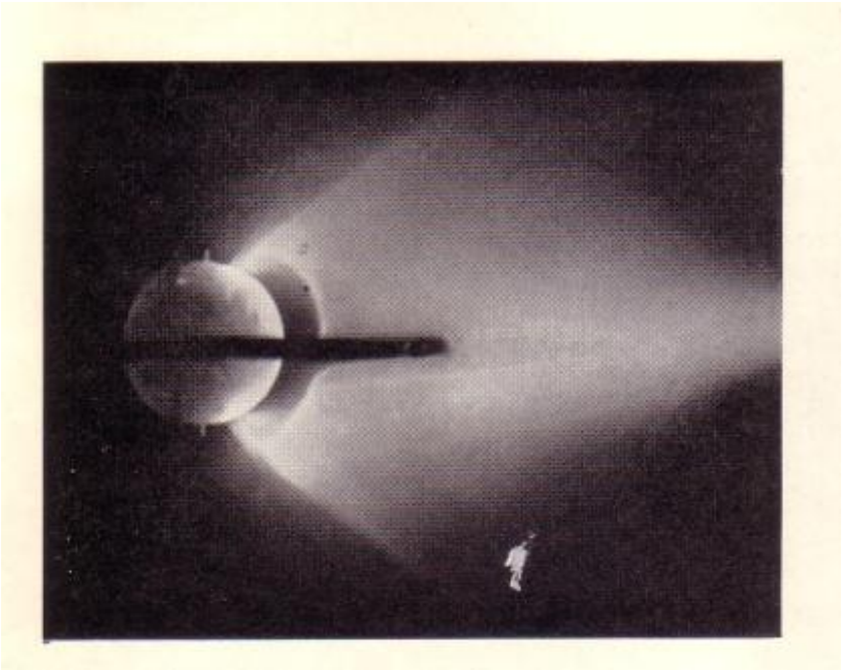
Why a Ring Current?

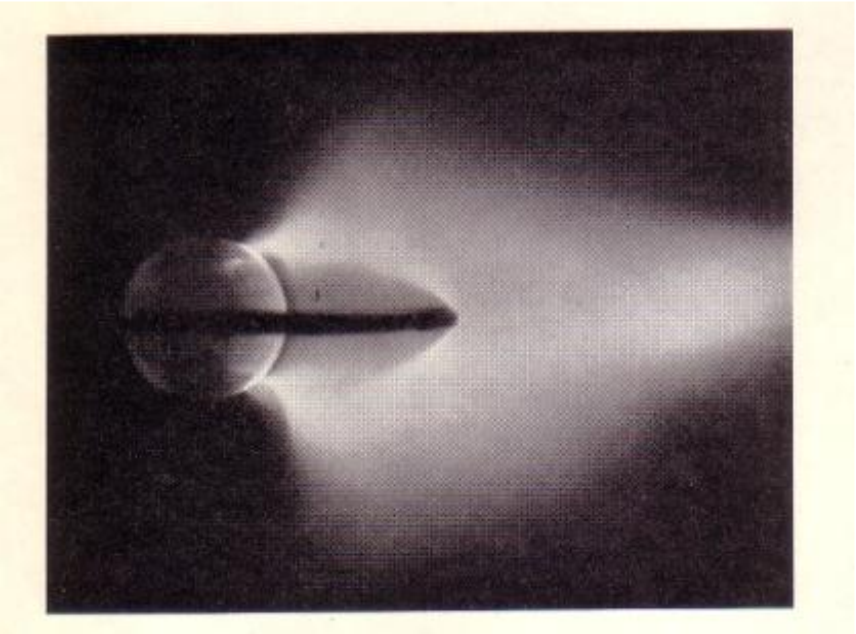


Birkeland's terrella with the auroral zones simulated as rings of bright optical emissions around both poles when the magnetized spheres is bombarded with energetic electrons. Right: Størmer trajectories of energetic electrons that impact the Earth's upper atmosphere.

Excellent agreement between Birkeland's laboratory simulations and Størmer's calculations.

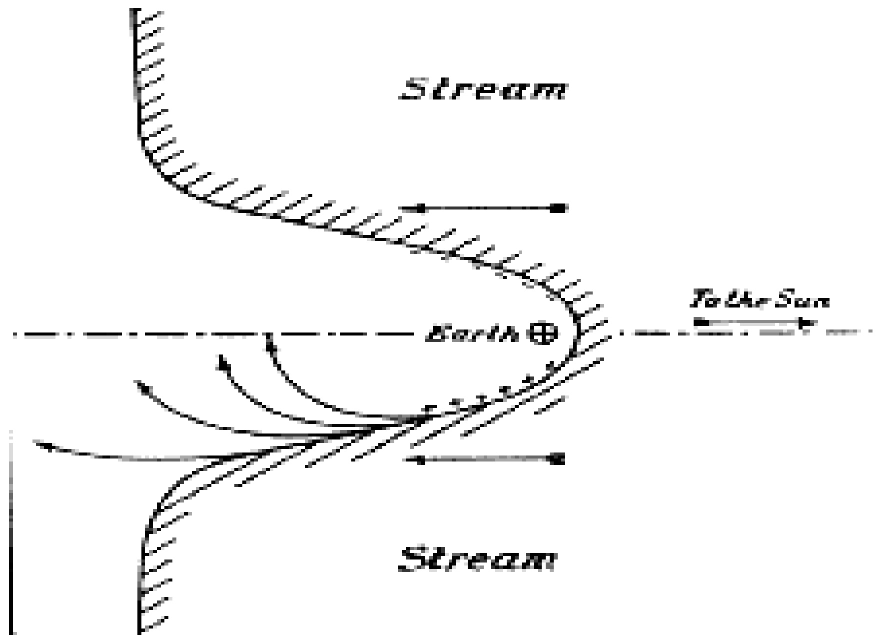
Why Space Physics?





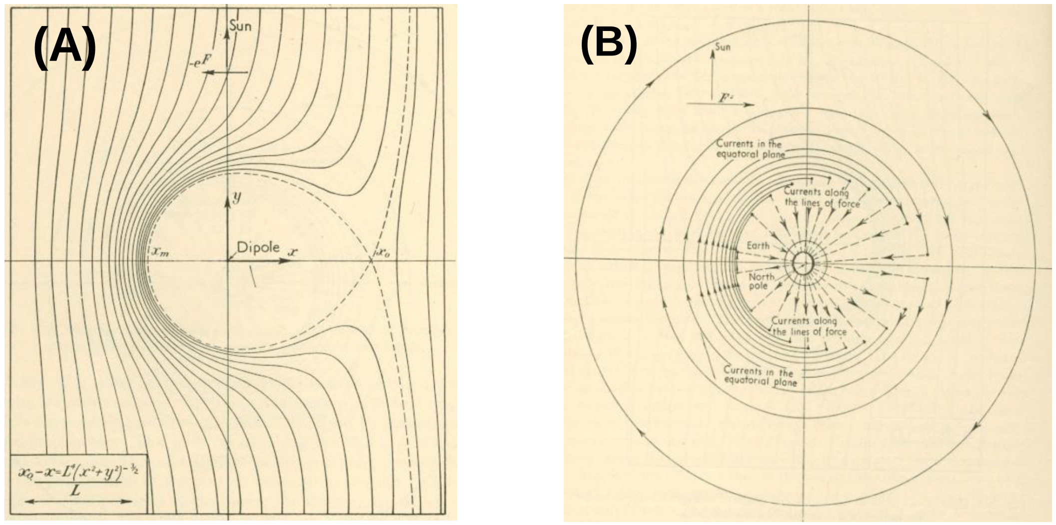
Ernst Brüche's version of Birkeland's terrella simulations with electric currents added. The current in the equator plane is turned off/on in the left /right picture. They illustrate that the ring current moves the auroral zones toward the magnetic equator [Brüche, 1930].

Why Space Physics?



The formation of the Chapman-Ferraro cavity. Arrows indicate paths of ions and electrons accounting for the ring current's formation.

Why a Ring Current?



Alfvén's concept of: (A) Energetic electron drift paths in the equatorial plane of a dipolar magnetic field with a uniform dusk-to-dawn, and (B) the resultant ring current in the equatorial plane. Note that Alfvén's ring current is highly asymmetric requiring that it close through the auroral ionosphere via magnetic field-aligned currents.

Why a Ring Current?

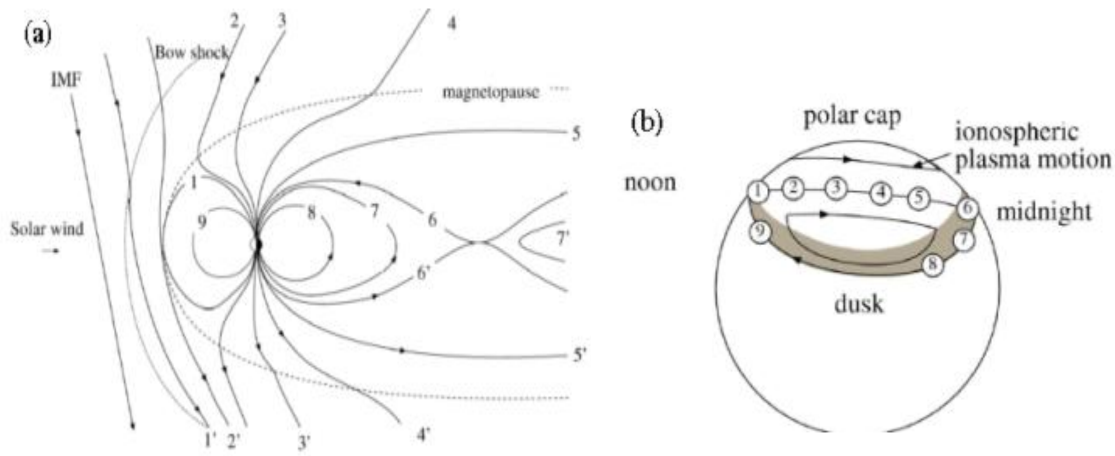
- At the dawn of the space age the C-F model presented the picture of a sporadic solar wind activated during solar flare events on the Sun.

- *Parker* [1958] suggested that a supersonic solar wind always flows from the Sun

- *Singer* [1957] model of ring current.

- Mariner and Explorer satellites in transit to Venus discover permanent solar wind [*Snyder and Neugebauer*, 1964] with an embedded solar wind [*Coleman et al.* 1960].

Why a Ring Current?



Schematic of Dungey's model applied to: (a) the magnetosphere, and (b) the high-latitude ionosphere.

Numbers 1 through 9 can be viewed as either a snapshot of nine representative field lines in the convection pattern or as the history of a given field line as it passes through the Dungey cycle, anti-sunward across the polar cap and sunward through the auroral (grey) ionosphere.

Why a Ring Current?

- **Ion spectral measurements by the U. of Iowa LEPEDEA experiment on OGO 3 indicated that the ring current particles originated in the plasma sheet [*Frank*, 1967].**

- **Results confirmed by ion measurements from Explorer 45 and consequent modeling of guiding center motions of low energy protons in the magnetotail [*Ejiri*, 1978].**

Case solved? Not quite!

- **Don Williams presentation at CRESS mission requirements meeting at AFRL in January 1981: O^+ ions provide about half the energy of ring current ions.**

- **Outstanding question: what force accelerates O^+ ions from a few <u>tenths</u> of 1 eV in the ionosphere to > 10 keV in the magnetosphere?**