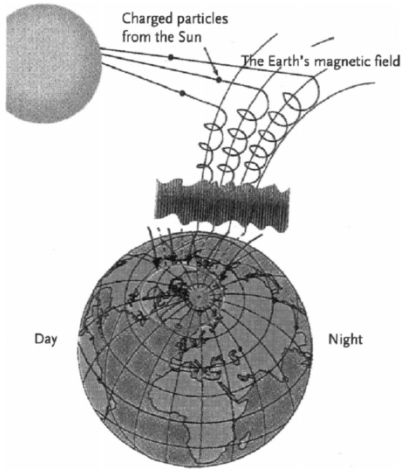
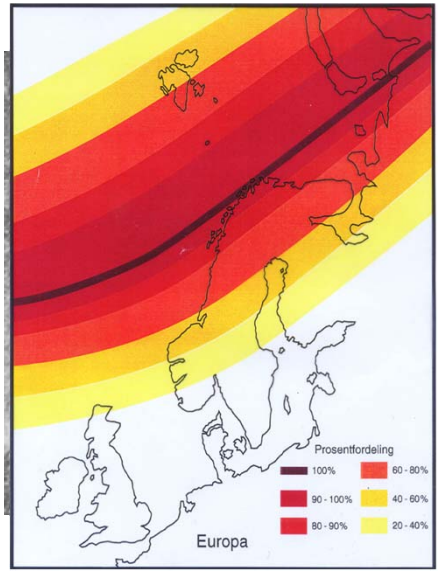
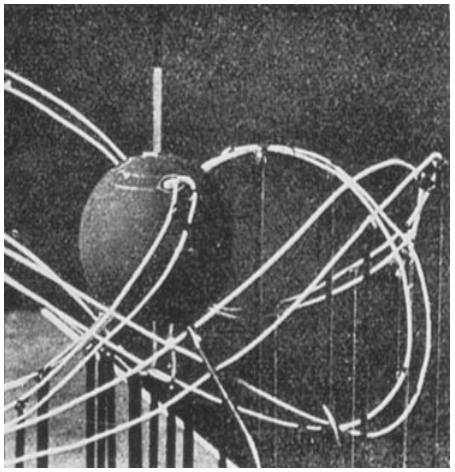
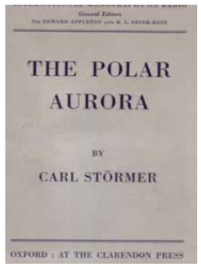




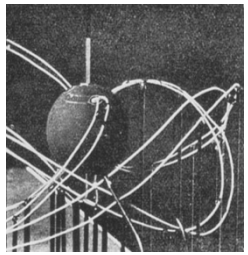


Carl Størmer's Auroral Accomplishments and Legacy:
A Space-Age Perspective

Alv Egeland
University of Oslo
and
William J. Burke
Boston College



Størmer's Auroral Accomplishments and Legacy:
A Space-Age Perspective



Introduction

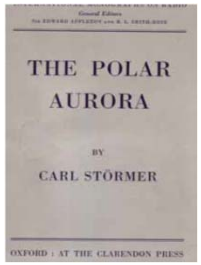
- Carl Størmer (1874 – 1957) made major pioneering contributions to our understanding of auroral physics concerning the:
  - Auroral heights –fixed by triangulations, and its dynamic morphologies
  - Specification of trajectories allowed energetic charged particles in the Earth's magnetic field.

- Størmer's auroral imaging contribution are discussed in another presentation; here we concentrate on his calculations of energetic particles trajectories.

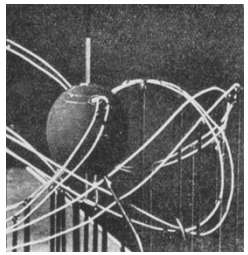
- Størmer - an unlikely giant in auroral physics, who never took a physics course.

- At critical points Størmer was influenced by Kristin Birkeland (1867 - 1917). Jacob Clay (1882 - 1955) [cosmic rays] and auroral physics by S. Chapman

- **Størmer saw implications whose impacts continue to this day.**



Størmer's Auroral Accomplishments and Legacy:
A Space-Age Perspective



Curriculum Vitae:

1898: Graduated *summa cum laude in mathematics* from University of Kristiana.

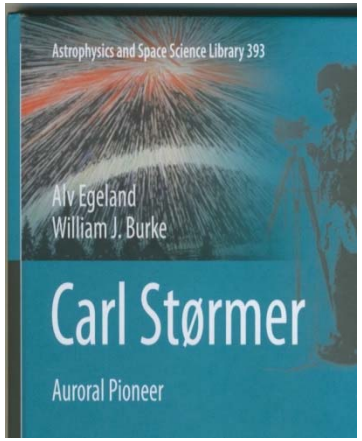
1903: Apppointed professor of Pure Mathematics at University of Kristiania.

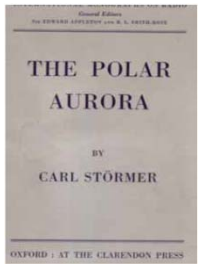
1903-1957: Auroral research, cosmic rays, and ring current hypothesis

1957: Died in Oslo, 83 years old. Active in auroral research up to the time of his death.

Published ~ 300 scientific papers (2 in botany, 20 in pure matematics)
3 books, including T*he Polar Aurora* with more than 400 pages.

Størmer at 20





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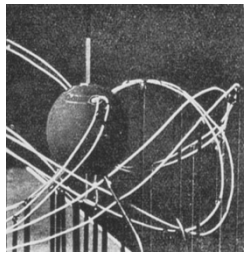
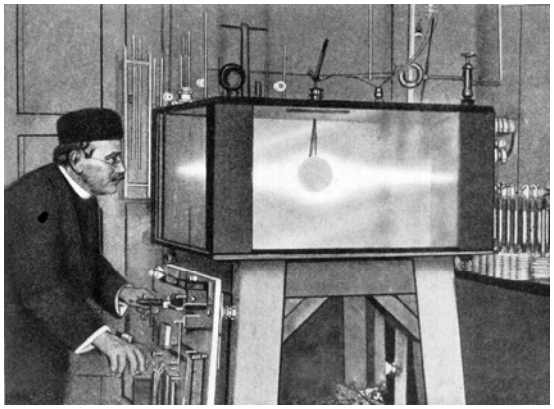
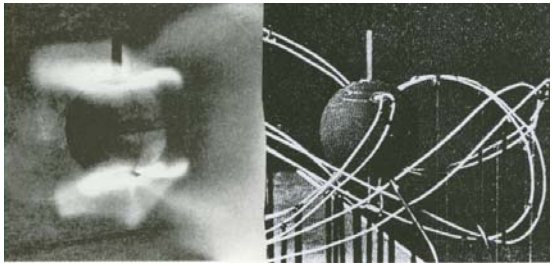
A Space-Age Perspective



Terrella Experiments and Trajectories

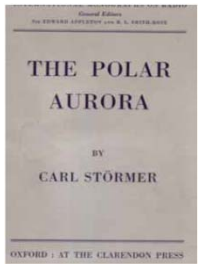


Birkeland experimenting

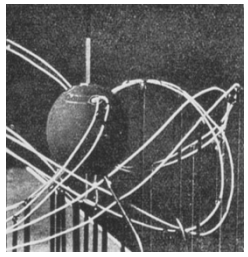


Terrella aurorae **Størmer trajectories**

- **Birkeland had followed Carl's progress during post-graduate studies with Poincaré in Paris.**
- **Professional collaboration began when the mathematical accuracy of a Birkeland publication was challenged (1898).**
  - **Størmer demonstrated its correctness.**
- **In 1903 Birkeland showed Størmer his terrella device and asked him to apply his mathematical skills to calculate electron trajectories in a dipole field, something that had never been accomplished before.**
- **Recognizing that the equations of motion had no analytic solutions, Størmer devised numerical methods on which he and his assistants would spend > 30,000 hours (~ 15 MY) solving them with a mechanical hand calculator!**
- **A comparison between the terrella results and Størmer's calculations are shown to the left. Birkeland was pleased.**



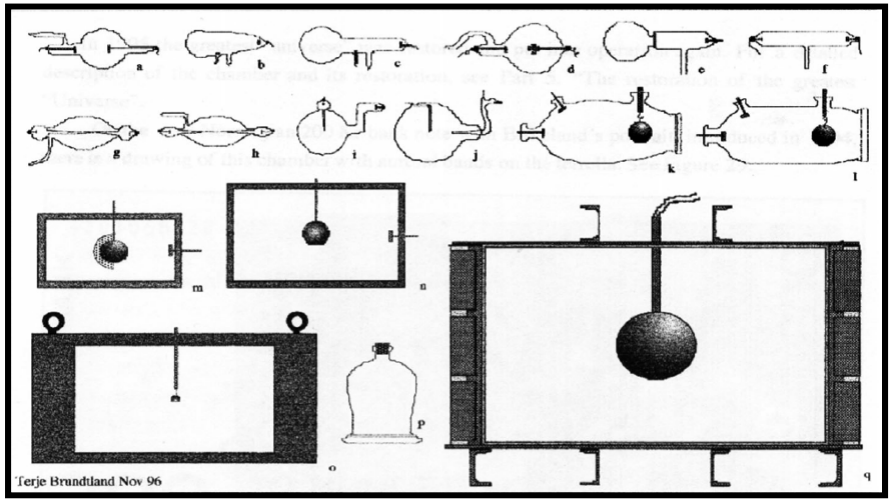
Størmer's Auroral Accomplishments and Legacy:
A Space-Age Perspective

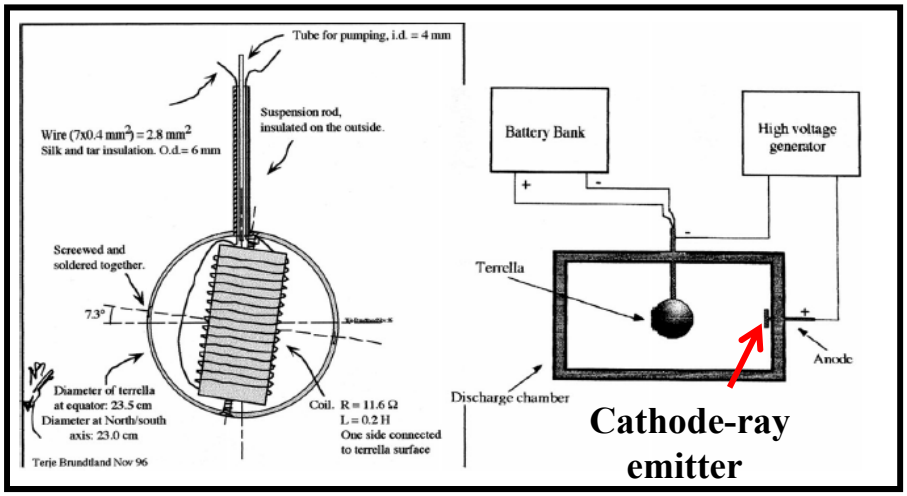


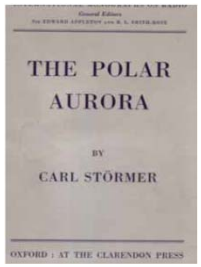
- During the 1890s and early 20th century Kristian Birkeland experimented with a electrical discharged devices that evolved into the terrella by means of which he simulated aurorae as caused by energetic solar electrons penetrating the Earth's magnetic field into the upper atmosphere.

- Terrellas consist of metal spheres in vacuum chambers and high-voltage cathode ray sources of electron beams.

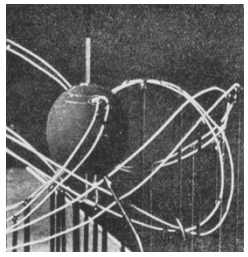
- The Earth-like spheres contained:
  - Embedded current-carrying coils to simulate the Earth's magnetic field
  - Phosphorescent t. surfaces to identify electron impact locations







Størmer's Auroral Accomplishments and Legacy:
A Space-Age Perspective



Størmer's Mathematical Techniques

1. **Took advantage of azimuthal symmetry of dipole fields by projecting particle motions onto magnetic meridional planes.**

2. **Recast the equations of motion for charged particles to represent trajectories as functions of spatial distance (ds) rather than time (dt) via transformation**

In spherical coordinates

$$\frac{d}{dt} = \frac{ds}{dt}\frac{d}{ds} = v\frac{d}{ds}$$

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

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

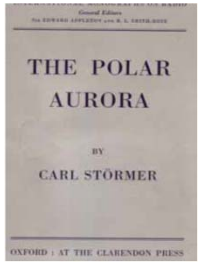
analogous to a particle's motion in a potential well

3. **Solving the equations of motions numerically, Størmer identified:**

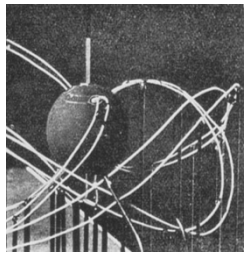
(A) A natural unit of length: $r_S^2 = |e|\, M / m\, v$ (Størmer length) , where M is the terrella/terrestrial magnetic dipole moment, e, m and v are the particle's charge, mass and speed, respectively.

(B) A parameter called magnetic stiffness or rigidity $B\rho = mv\,|e|$, where B is the local field strength and ρ is the particle's gyro-radius.

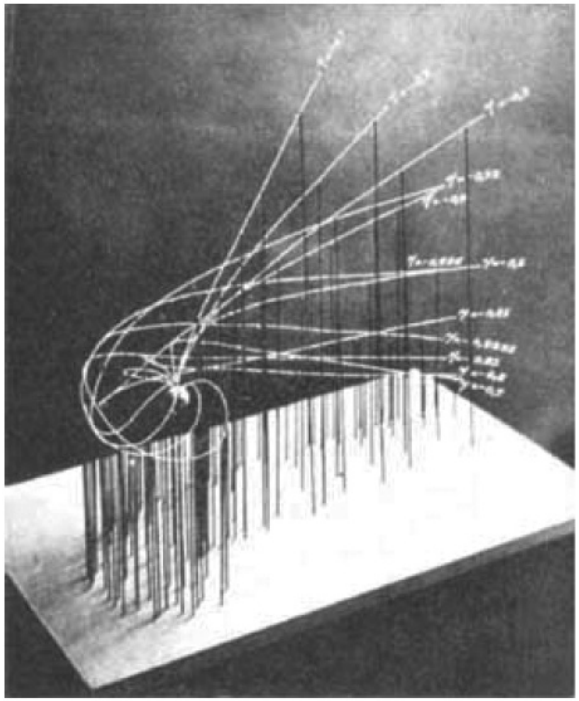
(C) A dimensionless constant : γ => *ratio of particle's angular momentum divided by the Earth's magnetic moment* . $|\gamma|$ *is* very small for auroral particles and of order 1 for cosmic rays.

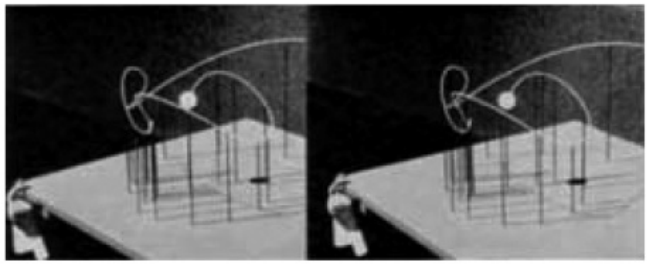


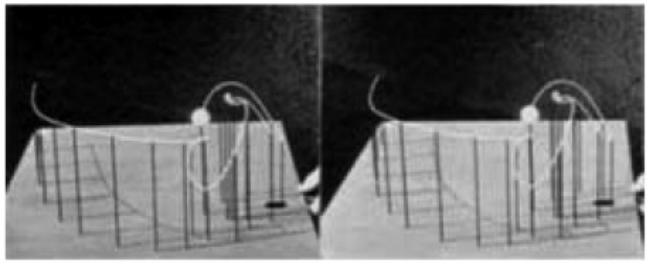
Størmer's Auroral Accomplishments and Legacy:
A Space-Age Perspective



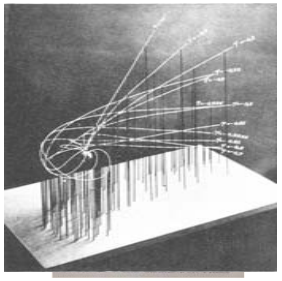
Størmer's Auroral Trajectories with Different Values of γ



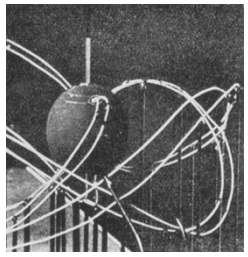




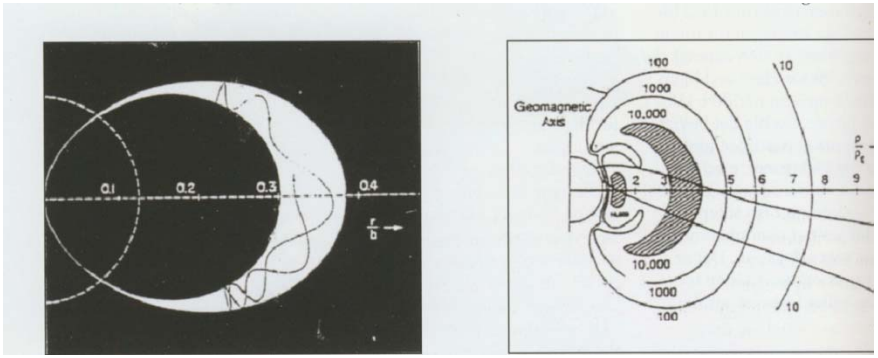
Wire models created by Størmer to illustrate complex. three-dimensional trajectories followed by energetic particles with different γ values that approach Earth from the sunward side and impact the nightside auroral ionosphere. (One p. theory- objections)

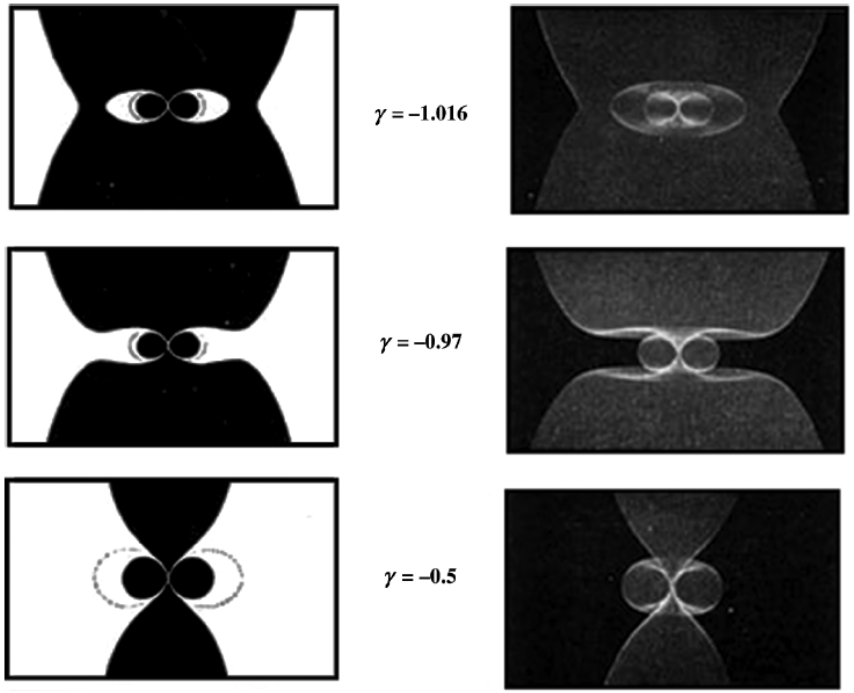


Størmer's Auroral Accomplishments and Legacy:
A Space-Age Perspective



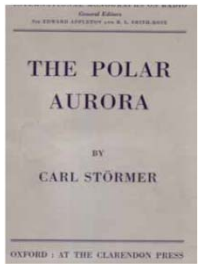
Størmer's Allowed and Forbidden Regions of Access



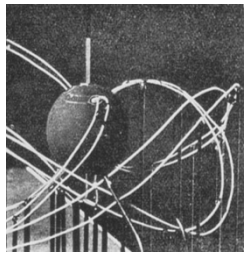


Schematics of energetic charged particles trapped near Earth by the magnetic field as envisaged by Størmer (left) and by James Van Allen (right) in what today is referred to as the radiation belts

γ = - 1.016 case is reminiscent of inner radiation belt discovered during the Explorer 1 – 3 missions, now regarded as debris from high energy cosmic rays.



Størmer's Auroral Accomplishments and Legacy:
A Space-Age Perspective



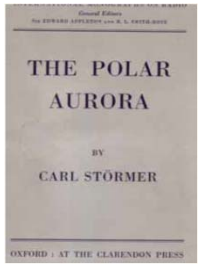
Cosmic Ray Source Problem

- Air not a perfect insulator.

- Hess' 1912 balloon experiments showed ionization rates increase with altitude => Extraterrestrial source, probably X- or gamma rays.

- Jacob Clay monitored cosmic ray intensities during 1927 boat trip from Genoa to Indonesia. => Cosmic ray intensities decrease with decreasing magnetic latitude.
  - Clay, J. (1927), Penetrating Radiation I, *Proc. Royal Acad. Sci. Amsterdam, 30*, 1115–1127.
  - Clay, J. (1928), Penetrating Radiation II, *Proc. Royal Acad. Sci, Amsterd*am, 31, 1091–1097.

- Størmer paid little attention to cosmic rays before Clay's papers came to his attention => immediately recognized that latitude effect could only be explained by cosmic rays being very energetic particles with trajectories were anticipated in his earlier calculations.
  - Størmer, C. (1931), Über die Probleme des Polarlicts, *Ergebn. Kosm. Phys,* Leipzig. Størmer (1955 • p. 375) The objections against my theory etc.



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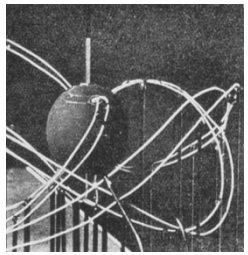
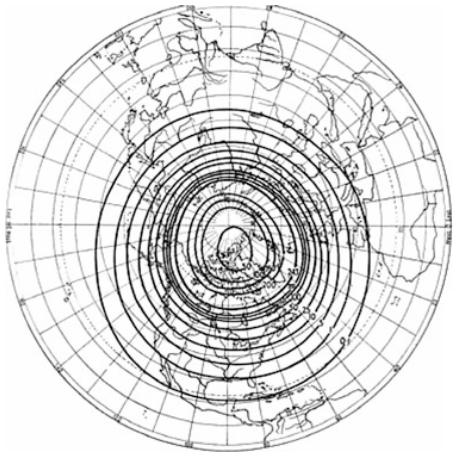


Hermann Fritz
***Das Polarlicht* (1881)**

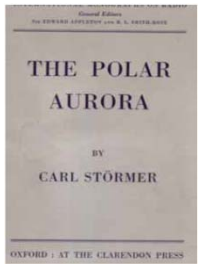


The Ring Current Hypothesis

- Based on historical research in the 1870s, Fritz developed a northern hemisphere *isochasmic* map, i.e. lines of equal probability for overhead aurorae, in magnetic latitude-longitude coordinates.
- Most probable auroral colatitude 23° / Terrella aurorae ??
- Neither Birkeland's terrella experiments nor Størmer's calculations replicated his own sightings of visible aurorae even near 33° colatitude.
- "Why? Where did he and Birkeland go wrong?"
- Was a steady dipole magnetic field a mistake??

•They failed to appreciate the effect of real field dynamics
• and energetic particle access to the ionosphere?

Schröder, W. (1998), Hermann Fritz and the foundation of auroral research, *Plan. Sp. Sci.*, 46, 461 – 463.



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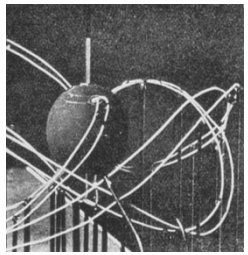


The Ring Current Hypothesis

- Discrepancy between auroral observations and the terrella/trajectory analyses, Stormer recalled : Birkeland saw faint glows near the terrella'sequatorial plane, on the night side.

- ***Størmer*** **(1911) suggested that energetic electrons had been trapped between two forbidden regions. Their combined eastward motions act like a westward ring of current that affects magnetic fields encountered by solar electrons and thus their trajectories.**

$\gamma = -1.016$

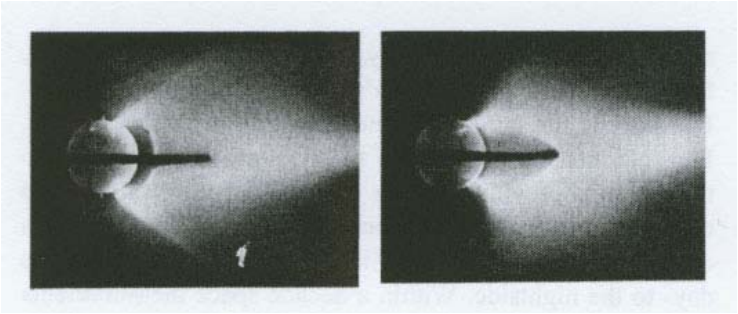
- Størmer 's numerical calculations showed that:

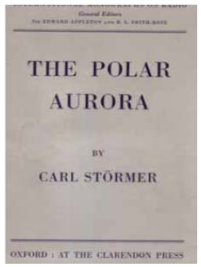
  (1) If the ground perturbation are ~ 30 nT, the discrepancies between the terrella's and auroral co-latitude vanish.

  (2) If the ground pertubations reach ~ 300 nT, auroral locations reach the 33° co-latitude of Oslo.

- In 1931 Ernst Brüche replicated Birkeland's terrella experiment, but indroduced a variable current source in the equatorial plane.

- Brüche's photographs show how auroral latitudes shift between when ring current is tuned off (left) and on (right) confirming Stormer's conjecture.





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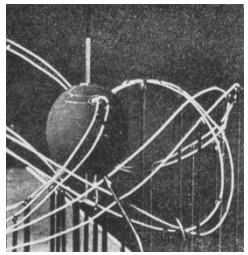


The Ring Current Hypothesis

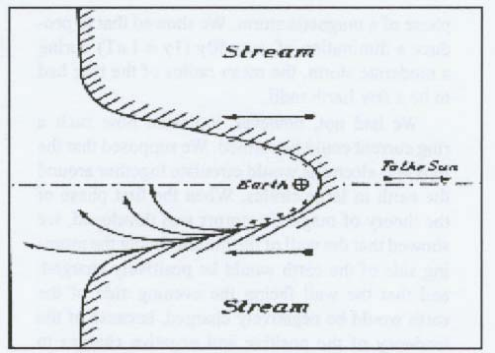
- *Chapman and Ferraro (*1932) [adapted Størmer's ring current hypothesis?] to explain the development of magnetic storms' main phases.

  - Intermittent streams of energetic solar protons enter the compressed terrestrial magnetic field on the dawn side

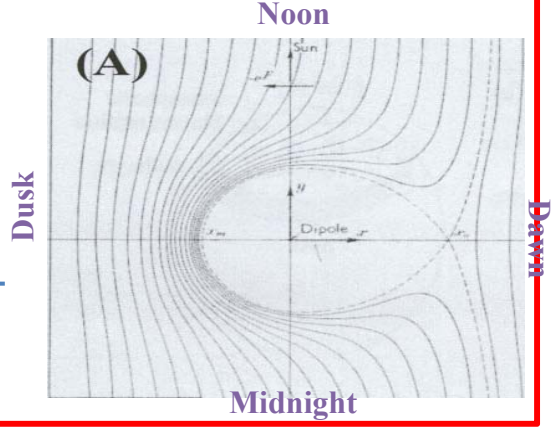
  - Their westward drifts provide the ring of current that produces characteristic negative perturbations on the ground.

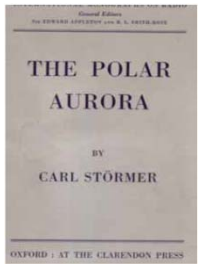
- In 1955 Hannes Alfvén applied the concept of guiding-center to drifts while developing a model in which the ring-current is carried by energetic solar electrons that enter the magneto-sphere on the dayside and drift eastward around the Earth.

Chapman-Ferraro Model



Alfvén Model





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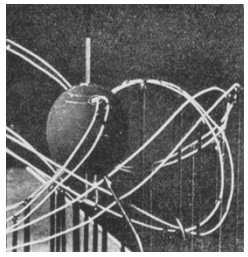
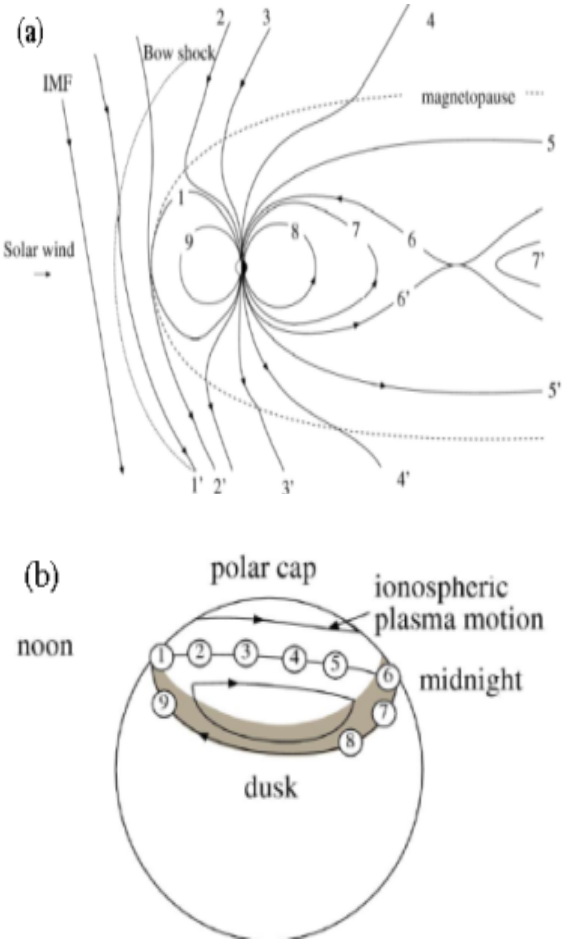
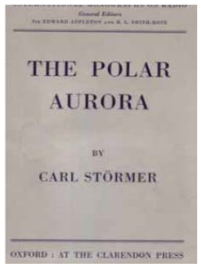


The Ring Current Hypothesis

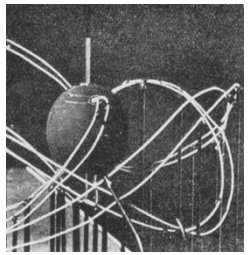
- Early Mariner and Explorer missions to Venus confirmed the presence of a permanent, supersonic wind and unexpectedly discovered an embedded interplanetary magnetic field that radically altered space age perspectives.
- The *Dungey* (1961) model indicated that ring current particles are energized as they drift earthward from the nightside.
- Plasma sheet protons seemed to have the ring-current spectral characteristics needed to be its source [*Frank*, JGR 1967].
- However, mass spectrometry measurements from ISEE clearly indicate that O^+ ions from the ionosphere constitute a significant fraction of the main phase ring current.
- Also, space-based measurements show that Region 1 field-aligned currents and cross-tail current sheets are major contributors to main-phase perturbations encapsulated in the Dst index [*Tsyganenko and Sitnov*, JGR, 2005].

The Dungey Model





Størmer's Auroral Accomplishments and Legacy: A Space-Age Perspective

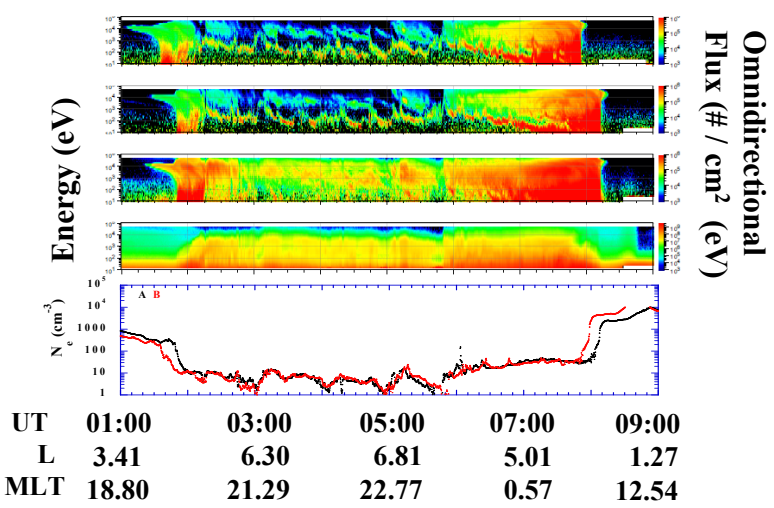


The Ring Current Hypothesis

- Early 1980s : the Sun not the sole source of ring current ions.
- O+, from the ionosphere can - the dominant ring current species?

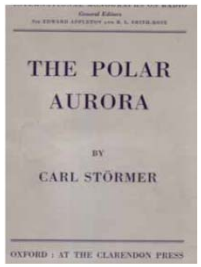
- *Keika et al.*, (JGR, 2013) review clearly demonstrates how O+ achieves as a ring current contributor.

- HOPE instrument on the Van Allen Probes offers the first *in situ* look at evolving mass composition of the stormtime ring current.



HOPE measurements during 1 June 2013 storm

- Both O+ and p+ found in ring current nose structure seen inside plasmapause.
- O+ with field-aligned fluxes indicate conics feeding in new particles into the plasma sheet
- O+ conics found in all storm's main phase, but not during initial or recovery phases



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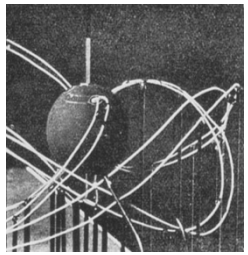

Summary and Conclusions

- Størmer's reflections on the physical significance of his trajectory calulations led to our first understanding of: (1) **cosmic rays** including rad. belts and, (2) the need for a **time-varying ring current** to explain observed auroral latitude distributions.

- Even a century later, Størmer's postulate of the ring current's existence (1911,) remains impressive. It also stimulated pioneering giants such as Chapman and Alfvén to think along new lines.

- When Space Age arrived our generation of scientists had a set of ready-made problems to address. Some of these problems continue to puzzle us even to this day.

- Outstanding ring-current related issues:

  - How is O+ accelerated from < 1eV in the ionosphere to > 10 keV in the magnetosphere?

  - What ratios of charge exchange, particle precipitation, and drift-path loss is responsible for ring current decay duriong the recovery phase of magnetic storms?