Appendixes

Appendix A: Størmer's Trajectory Analyses

This appendix provides a simplified derivation of the principles governing which set of trajectories are allowed or forbidden for charged particles moving in dipolar magnetic fields. Although the derivation makes the same assumptions as Størmer and follows the general lines of his argument in the Geneva papers (*Størmer*, 1911, 1912), we decided to adopt a set of notation that is more familiar to present day physicists than was used early in the twentieth century. Readers with technical and/or historical inclinations can find an extended description in Størmer's early chapters of *The Polar Aurora*, Part II.

The force exerted by a time stationary magnetic field $\vec{B}(\vec{x})$ on a particle with mass m, charge q and moving at a velocity $\vec{v} = d\vec{x}/dt$ is,

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

Since magnetic forces are exerted perpendicular to the charged particle's velocity, its speed v, momentum p = mv and kinetic energies $E_k = ½\ mv^2$ are constant along the trajectory.

Størmer approximated the magnetic field as an Earth-centered dipolar whose axis points along the planet's axis of rotation. We define a system of coordinates whose origin is at the center of the dipole and ±z direction aligns with the Earth's spin axis. Expressed in spherical coordinates the magnetic field is

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

Here M is the dipole moment of the Earth's magnetic field, r is the distance from the origin to $\vec{x}$ the particle's location; $\hat{r}$ and $\hat{\theta}$ represent unit vectors in the directions of increasing radial distance and colatitude, respectively. The energies of the auroral particles are so small that relativistic effects can be ignored. Following Birkeland, Størmer thought that auroral particles impacting the upper atmosphere came directly from the Sun. Electrons and protons that take about 30 h to reach Earth

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must travel with speeds near 1,000 km/s, much less than the 300,000 km/s speed of light. Fully relativistic Størmer equations for cosmic-ray trajectories, are derived by *Rossi and Olbert* (1970).

Solving a particle's trajectory in a specified force field, we normally follow its temporal development. However, Størmer took a different tack, by transforming (A.1) into the spatial domain. Small steps in distance along a trajectory (ds) is represented in spherical coordinates as

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

or equivalently

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

Two points should be kept in mind. First, the left side of the equation describes the trajectory path's projection into a magnetic meridional plane. Second, Størmer argued that (A.3) can be viewed as analogous to the motion of a particle moving in a potential well. The terms on the left side of the equation are analogous to a particle's kinetic energy; the term $\left(rSin\theta\frac{d\phi}{ds}\right)^2$ acts like a potential energy barrier. As such it dictates where a particle of given energy may or may not move in a potential well. To understand this analogy we must represent (A.1) in the spatial-domain via the transformation $\frac{d}{dt} \to \frac{ds}{dt}\frac{d}{ds} = v\frac{d}{ds}$. Applied to (A.1) this transformation yields

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

Størmer used meridional planes rather than three dimensional space. We next consider the scalar product of (A.4) with the quantity $\hat{e}_3 \times \vec{x} = rSin\theta\hat{e}_\phi$, where $\hat{e}_3$ and $\hat{e}_\phi$ are unit vectors in the directions of increasing z and azimuth ϕ. The left side of the equation becomes

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

The right side of (A.4) is

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

Using the requirement that, $\nabla \cdot \vec{B} = 0$, it can be shown that for an axial-symmetric field

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

where

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

is the magnetic flux radially crossing the surface of a sphere with radius r between the pole and co-latitude θ. Combining (A.7) and (A.5) we can rewrite (A.4) as a perfect derivative:

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

The quantity in brackets must be some constant C and,

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

Substitution into equation (A.3) gives

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

While (A.9) provides guidance for understanding the potential well in which charged particles move, it applies to any magnetic field that has axial symmetry, such as Poincaré's monopole. For a magnetic dipole the magnetic flux term must be specified. This is done by combining (A.2) with (A.7) to obtain

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

Thus, in the case of a dipolar magnetic field (A.9) becomes

$$\left(\frac{dr}{ds}\right)^2 + \left(r\frac{d\theta}{ds}\right)^2 = 1 - \left(\frac{q}{p}\right)^2\cdot\left(\frac{C + M\cdot Sin^2\theta/r}{rSin\theta}\right)^2. \tag{A.11}$$

Before seeking solutions of (A.11) it is useful to consider the geometry of the trajectory near the point$\vec{x}$. The figures in Rossi and Olbert (1970) contain sketches of two planes with pale blue and black outlines. They represent the magnetic meridional plane and the plane containing the local trajectory (dark blue line) in 3-dimensional space. The pale green line shows the projection of the trajectory onto the magnetic meridional plane. The term $rSin\theta\frac{d\phi}{ds}$ has a geometric interpretation as the component of $\frac{d\vec{x}}{ds}$ perpendicular to the magnetic meridional plane. This is equal to the Sine of the angle χ between the meridional plane and the trajectory at its intercept. That is

$$Sin\chi = rSin\theta\frac{d\phi}{ds} = \left(\frac{q}{p}\right)\cdot\left(\frac{M\cdot Sin\theta}{r^2} + \frac{C}{rSin\theta}\right) \tag{A.12}$$

This equation was first obtained by Størmer and is called the Størmer integral. This expression can be simplified by introducing the Størmer distance $r_S^2 = qM/p$ and the function

$$h\left(\frac{r}{r_S},\theta\right) = \left(\frac{r}{r_S}\right)^2 Sin\theta + \left(\frac{r}{r_S}\right)\cdot\frac{2\gamma}{Sin\theta} = Sin\chi. \tag{A13}$$

The new term, $\gamma = \left(\frac{Cr_S}{2M}\right)$ is a constant that Størmer pointed out can range between + and $-\infty$. The equation of motion can finally be written

$$\left(\frac{dr}{ds}\right)^2 + \left(r\frac{d\theta}{ds}\right)^2 = 1 - \left[h\left(\frac{r}{r_S}\theta\right)\right]^2. \tag{A.14}$$

The implications of (A.14) are clear. The left side of the equation consist of two quantities that are positive definite. The right side of the equation can meet this requirement only if $\left|h\left(\frac{r}{r_S},\theta\right)\right| \leq 1$. If $\left|h\left(\frac{r}{r_S},\theta\right)\right| > 1$ the right side of the equation becomes negative and trajectories in the meridional plane become imaginary numbers. Thus, charged particles in a dipole field can only access regions of space where $|h| \leq 1$; otherwise the region of space is forbidden. Størmer realized that with this simple discriminant he could identify regions of space into which particles can/cannot penetrate. As particles approach forbidden regions, they do not slow down; their speeds are constant. Rather the magnetic barrier deflects them back into allowed regions of space (cf. also Rossi and Olbert, 197; pp. 23–120).

Knowing a general principle and seeing how that principle is actualized in the real world, are quite distinct. The early chapters of Part II of *The Polar Aurora* are filled with examples that Størmer worked out in order to bridge these two levels of understanding. Hopefully the outline leading to (A.14) will help readers understand how the ever-persistent Carl Størmer approached the monumental task of tracking energetic charged particles through dipolar magnetic fields.

In analyzing the motions of charged particles in the Earth's magnetic field, before the magnetosphere was identified, Størmer recognized a useful parameter now called the "*Størmer length (C_{ST})*", which in centimeters is defined:

$$C_{\mathrm{ST}}(\mathrm{cm}) = (\mathrm{M/B}\ \rho)^{1/2}$$

where $\rho = mv/qB$ is the trajectories' local radius of curvature. Thus, C_{ST} can be expressed equivalently

$$C_{\mathrm{ST}}(\mathrm{cm}) \ = (Mq/mv)^{1/2}.$$

The symbols q, m, and v, respectively represent the charge, mass and speed of the energetic charged particle. When considering the trajectories of charged particle in the field of a magnetic dipole two categories are important: cosmic rays with typical energies >1 MeV and auroral particles with energies <30 keV. For a proton $\rho\ (\mathrm{cm}) = 144 \cdot [E(\mathrm{ev})]^{1/2}/B\ (\mathrm{G})$. The ratio of curvature radii for a 1 MeV and a 30 keV proton is 5.77, and the ratio of Størmer lengths is 0.42. Since $M \approx 8 \cdot 10^{25}$ G-cm^3, C_{ST} for a 1 MeV proton in a 0.05 G field is ~$2.36 \cdot 10^{10}$ cm ≈ 37 R_E. Conversely, under the same magnetic field conditions $C_{\mathrm{ST}} \approx 89$ R_E for a 30 keV proton. Thus, typical Størmer lengths for cosmic rays and auroral particles are smaller and larger than the linear dimensions of the magnetosphere, respectively. The trajectories of both particles are still referred to as Størmer orbits. We note that *Alfvén* [1950] introduced a perturbation method that considerably simplified the computation of their motions.

Mathematical References: Cf. Sect. 11.5

Appendix B: Auroral Height and Position Orientations

This discussion of formulas used to compute of auroral heights and orientations follows Størmer's presentation in *The Polar Aurora* with significant overlapping descriptions found in Harang's (1951) earlier monograph *The Aurorae*.

Størmer's parallactic analyses started with enlargements of 3 by 4 cm negatives and their projections onto pieces of white paper. The enlargement was such that that 1° on the negative corresponded to 1 cm on the screen. Contours of the imaged auroral form, the background star pattern and the centers of pictures were then marked on projected images. Performing this procedure simultaneously for both of parallactic pairs assured the greatest accuracy. The correct degree of enlargement was controlled by measuring the angular distances between known stars. To minimize distortions the reference stars were located near the pictures' centers. The angular distance between the two stars S_1 and S_2 (cf. Fig. B.1) could either be obtained from star catalogues or computed using the following formulas (*Harang*, 1951, p.15):

$$Tan\frac{a}{2} = Cos\left(\frac{B_1 - B_2}{2}\right) \cdot Sec\left(\frac{B_1 + B_2}{2}\right) \cdot Tan\left(\frac{\delta_1 - \delta_2}{2}\right). \tag{B.1}$$

As indicated in Fig. B.1, δ_1 and δ_2 are the declinations for the two stars, while B_1 and B_2 are the angles that the great circles through the stars make with their declination circles. The two projections were then placed on a light table and adjusted so the stars exactly covered each other. The auroral contours from the second station are drawn on the one from the main station. All further analyses were conducted using this combined map. The stars are therefore easily identified on the projections when using such maps. Still, with a large number of base-lines, the calculations for each observation required much work. Images containing three reference stars just one nomogram is needed. Størmer claimed that the accuracy achieved through this graphical method is better than 0.1°, and was sufficient for making parallactic measurements.

The schematic in Fig. B.2 is the simplest possible two-dimensional representation of the geometry used to estimate the height H of a point C on an auroral point

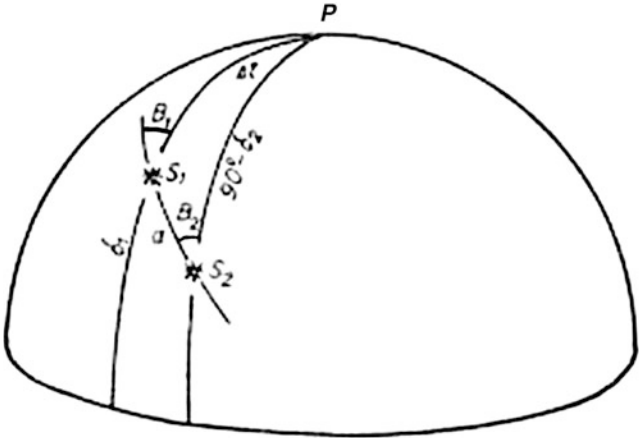

Fig. B.1 Earth-centered celestial hemisphere with the locations of two stars and their declinations marked

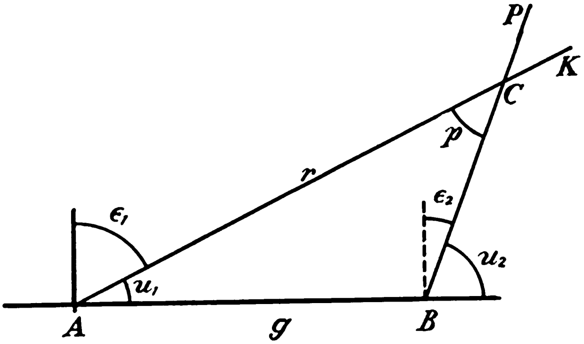

Fig. B.2 Flat-Earth schematic representation of method used to approximate the height of an auroral structure at point C when viewed from stations at points A and B separated by a distance *g* (Størmer, 1955, p. 47)

using measurements from two stations located at points A and B that are separated by a distance g (Fig. B.3). The parallax angle (p) between the lines extending from C to the two the auroral stations is $p = u_2 - u_1 = \varepsilon_1 - \varepsilon_2$. As indicated in Fig. B.2, the angles ε_1 and ε_2 are complement to u_1 and u_2, respectively. The distance between A and C, r is:

$$r = \frac{\mathrm{g\ Sin\ u_2}}{\mathrm{Sin\ p}} = \frac{\mathrm{g\ Cos}\ \varepsilon_2}{\mathrm{Sin\ p}}. \tag{B.2}$$

In this approximation $H = r\ Sin\ u_1$.

Figure B.3 illustrates the next level of complexity for making parallactic estimates of auroral heights. It shows a vertical section through the main auroral

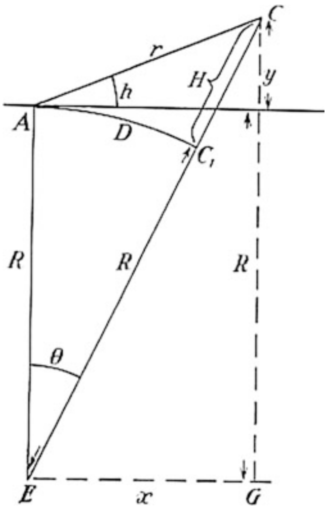

Fig. B.3 A circular-Earth schematic representation of method used to approximate the height (H) of an auroral structure at point C when viewed from stations at points A and C_1 separated by a distance D along the Earth's surface (Størmer, 1955, p. 48)

station A and the point of interest C on an auroral form. By construction define $x = r \, Cos \, h$ and $y = r \, Sin \, h$, where h is the angle between the horizontal tangent line at A and r. The height of the form above the Earth's surface is

$$H = \sqrt{(R + y)^2 + x^2} - R. \tag{B.3}$$

Here the symbol R represents the radius of Earth. Let D represent the distance along the Earth's surface between station A and a point C_1. If θ is given in degrees then

$$\mathrm{D} = \frac{\pi}{180} \, \mathrm{R} \, \theta \quad \text{and} \quad Sin \, \theta = \frac{x}{R + H}. \tag{B.4}$$

To calculate H and D in the general case, it is necessary to use spherical rather than planar trigonometric constructions. Here Stormer introduced three analogous spherical coordinate systems centered on station A:

1. *Coordinate System 1*: The axis of rotation passes from A toward the celestial north pole. As indicated in Fig. B.4 the coordinate system's two angles are the declination δ and the hour angle t. δ ranges between 90° and −90° at the north and south poles; $t = 0$ at the local meridian and has positive/negative values toward the west/east (Størmer, 1955, p. 50, Fig. 39).
2. *Coordinate System 2*: The axis of rotation passes from A toward local vertical. As indicated in Fig. B.5 the coordinate system's is defined by the altitude h and azimuth a angles. h ranges between 90° and −90° at the zenith and nadir, respectively; $a = 0$ at the local meridian and has positive/negative values toward the west/east (Størmer, 1955, p. 50, Fig. 38).

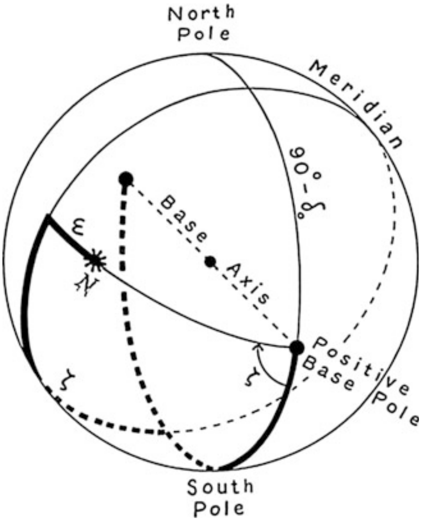

Fig. B.4 Schematic representation of spherical coordinate system 1 (Størmer, 1955, p. 50)

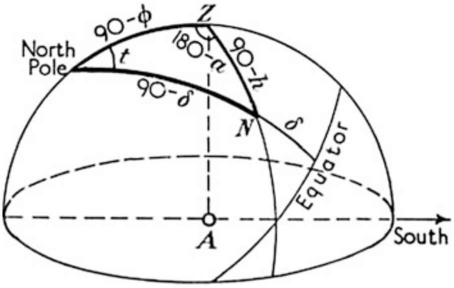

Fig. B.5 Schematic representation of spherical coordinate system 2 used in calculating the auroral height (Størmer, 1955, p. 49)

3. *Coordinate System 3*: The vertical axis of rotation passes from A toward the location of station B. As shown in Fig. B.6 this coordinate system is defined by angles ε and ζ that are analogous to δ/h and t/a in systems 1/2. ε ranges between 90° and −90° at the positive and negative poles. ζ increases in the direction of the arrow in Fig. B.4 and decreases in the opposite direction (Størmer, 1955, p. 49, Fig. 37). In Fig. B.6 the intersection between the celestial sphere and the baseline through the two auroral stations A and B, is called the positive base pole. The symbol N can represent the location of either a reference star or a point on the aurora as seen from A; δ_0 is the point's declination.

In *The Polar Aurora* (pp. 50 and 51) Størmer provides the equations needed to transform pairs of angles calculated in one coordinate system into another whose application proves more convenient. For practical use, interested readers should consult the original equations. Størmer also describes useful and rapid graphical methods for finding the angles of triangles on spherical surface from auroral plate measurements. Based on this method several networks which they used to determine the coordinates of the selected auroral points were worked out.

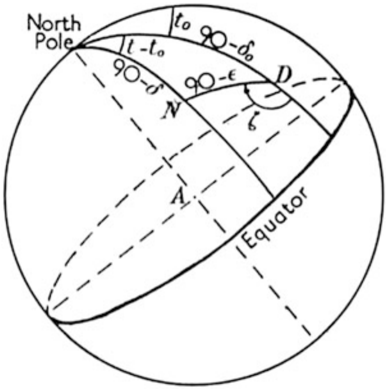

Fig. B.6 Schematic representation of spherical coordinate system 3 (Størmer, 1955, p. 49)

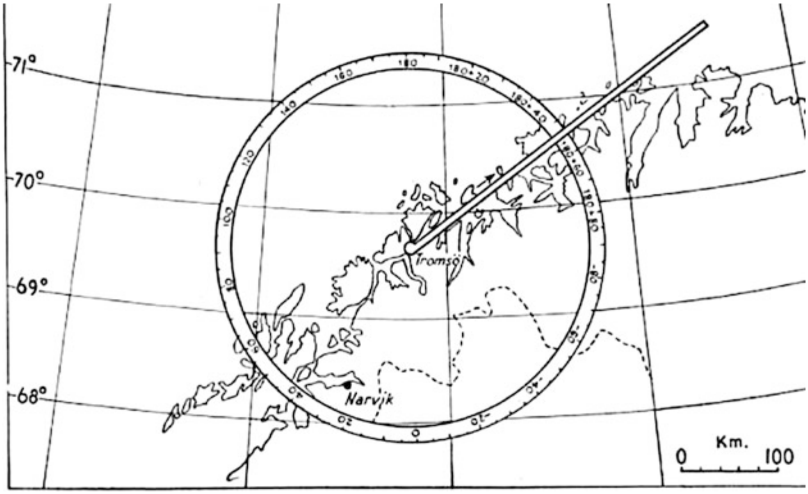

Fig. B.7 Illustration of graphical method used by Størmer to specify the geographical locations and orientations of auroral forms (Størmer, 1955, p. 63)

The orientations of auroral arcs and bands with respect to the local magnetic field were of special interest to Størmer. The simplest way to obtain the orientation of these forms was by a graphical method. The horizontal projections on the Earth's surface were marked onto a map after the azimuth *a* and the distance *D* had been determined. Cross-like images of the stars helped, because their arms point toward their centers. It was important that the optical axes of the projectors and centers of the projected points be the same. If the optical centers of the films from A and B are very near each other, the two sketches could be placed on top of each other with imaged stars coinciding. The geographical and geomagnetic orientations of the observed forms can easily be found. Figure B.7 shows Størmer's usual graphical aid for determining the horizontal projection of auroral forms.

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