3irkeland and the Electromagnetic Cosmology

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THE HISTORY of science is everywhere replete with controversies, peronal prejudices, and fierce animosities beween camps holding conflicting theoretical iews. In astrophysics, the iconoclastic eforts of Copernicus, Galileo, Subrahmanan Chandrasekhar, Fred Hoyle, and Halon Arp immediately spring to mind.

Lesser known among the disputes in asrophysics is the half-century-long controersy between the advocates of Kristian 3irkeland, who suggested that electron treams following the Earth's magneticield lines were responsible for auroras, ınd Sydney Chapman, who maintained hat the Earth was surrounded by "vacuım." It was not until 1974, three-quarters of a century after the theories were proposed, that space-probe measurements decided the controversy in Birkeland's favor.

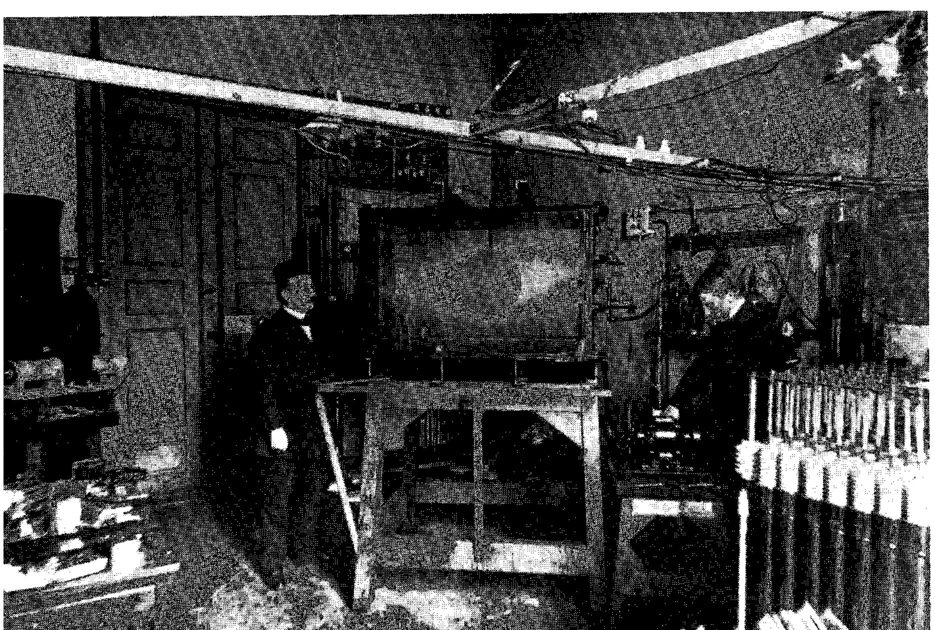
Today, plasma physicists believe that nany of the phenomena in the cosmos can be explained in terms of a spaghetti of 'Birkeland currents" (electrical currents lowing along magnetic lines of force; see Table I), and that "pinched" Birkeland currents may be the mechanism responsible for initiating the gravitational collapse of matter in the plasma state. However, it is not generally known that Birkeland, whom many regard as the founder of experimental astrophysics, had himself developed an extensive cosmological theory based upon his experiments.

Kristian Olaf Bernhard Birkeland (1867-1917) received his education in Bonn, Geneva, and Leipzig, studying under such notables as Henri Poincaré and Heinrich Hertz, and was appointed a professor at the University of Oslo in 1898, when he was 31. His remarkable achievements in technology and applied physics made him rich and famous (see Table II) and financed his auroral investigations.

The main point of his auroral theory was that electrically charged particles ejected from sunspots are captured by the Earth's magnetic field and directed along the field's lines into the polar regions. Because the particles are electrically charged, they can be deflected by the Earth's magnetic field in such a way that they arrive on the night side of the planet. As the incoming particles reach the upper atmosphere they are slowed down by the increasing density of atoms and molecules, and in the process the atmospheric constituents become excited and ionized. Birkeland performed extensive laboratory experiments to illustrate his points.

It was amazing that he could actually demonstrate the new theory. His basic idea was to study the motions of electrons in a magnetic dipole field where the air density is low. The experiment, labeled a "terrella," was a model of the conditions in Earth's upper atmosphere. In many ways it reminds us today of how a television picture is produced by energetic electrons striking a phosphor screen (*S&T:* December, 1982, page 534). At the turn of the century, Birkeland's work was considered to be state-of-the-art physics.

The terrella model was really rather simple. He placed a sphere containing an electromagnet inside a large vacuum chamber, which represented the space around the Earth and its magnetic field. He then shot clouds of electrons toward this simulated Earth to produce a light phenomenon that looked like the aurora. (We now



Birkeland, the founder of experimental astrophysics, is shown here with his assistant, K. Devik, and his "terrella," a magnetized metallic globe representing the Earth.

TABLE I

Phenomena in which Birkeland currents are thought to play a role:

***In situ* observations**

Auroral rays, arcs, and draperies
Auroral electrojet
Magnetospheric inverted V events
"Flux ropes" in ionosphere of Venus

Observations not accessible to *in situ* measurements

Solar prominences, spicules, coronal streamers, and polar plumes
Cometary tails (*in situ,* 1985)
Interstellar medium (e.g., Veil nebula)
Interstellar clouds (e.g., Lagoon nebula, Orion nebula)
Plasma within the galactic center
Lobes of double radio galaxies and galactic "jets"

TABLE II

Birkeland's other contributions to science and technology:

Derived the general expression for the Poynting vector
Gave the first general solution to Maxwell's equations
Pioneered the field of charged-particle beams
Utilized the concept of "longitudinal-mass"
Constructed the first foil diodes
Pioneered the field of visible-light photography of electrical discharges
Advocated charged-particle propulsion engines for space travel
Created Norsk Hydro's nitrogen-fertilizer industry (the Birkeland-Eyde method for production of potassium nitrate)
Invented an electromagnetic rail gun capable of firing a 10-kg projectile
Established Birkeland's Firearms
Anticipated cosmic rays (discovered in 1911) with his calculations involving energies of several billion electron volts
Held patents on the electromagnetic cannon, electric blankets, solid margarine, and hearing aids

know that the solar wind also consists of positive ions, as well as negative electrons.)

Birkeland could see that bunches of electrons curved down toward and around the Earth's poles. While the actual process is somewhat more complicated than he envisioned (see illustration on page 391), his results were surprisingly good. The electrons passing through space were captured by the Earth's magnetic field and followed spiral tracks about the lines of force; they were then guided onto the Earth's night side and, in the process of colliding with the gases in the neutral atmosphere, created the aurora.

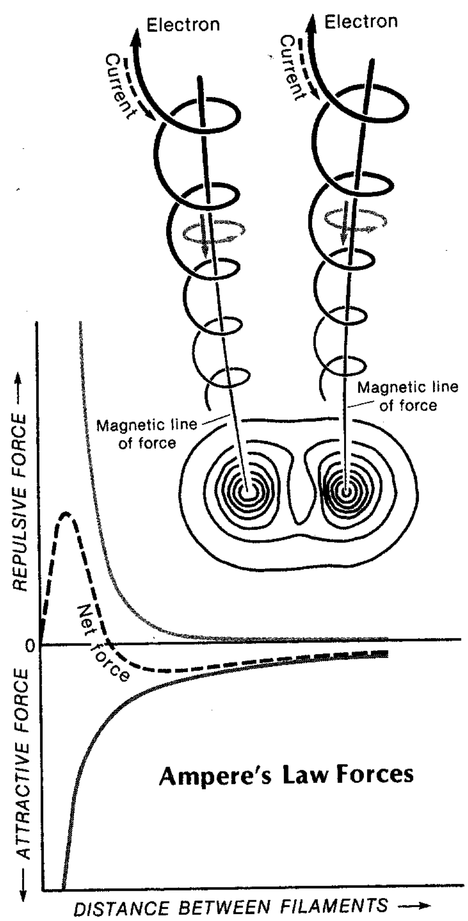
Birkeland believed that by varying his experimental parameters, his terrella could be made to represent the Earth, Saturn, the Sun, or a galaxy or nebula. In the preface to an account of his 1902-03 aurora expedition work, Birkeland wrote:

> . . . I have carried out a long series of experimental investigations with a magnetic globe in a large vacuum-box intended for electric discharges. I have hereby been enabled to obtain a representation of the way in which cathode-rays move singly, and group themselves in crowds about a magnetic globe such as this. . . . I will . . . refer to formulae by Oliver Heaviside, that the electrostatic repulsion between rays maintains the balance with the electro-dynamic attraction.
>
> The magnetic globe was then made the cathode in the vacuum-box and experiments were carried out under these conditions for many years. It was in this way that there gradually appeared experimental analogies to various cosmic phenomena, such as zodiacal light, Saturn's rings, sun spots and spiral nebulae.
>
> The consequence was that attempts were made to knit together all these new discoveries and hypotheses into one cosmogonic theory, in which solar systems and the formation of galactic systems are discussed perhaps more from electromagnetic points of view than from the theory of gravitation.
>
> One of the most peculiar features of this cosmogony is that space beyond the heavenly bodies is assumed to be filled with electrons and flying electric ions of all kinds in such density that the aggregate mass of the heavenly bodies within a limited, very large space would be only a very small fraction of the aggregate mass of the flying atoms and corpuscles there.

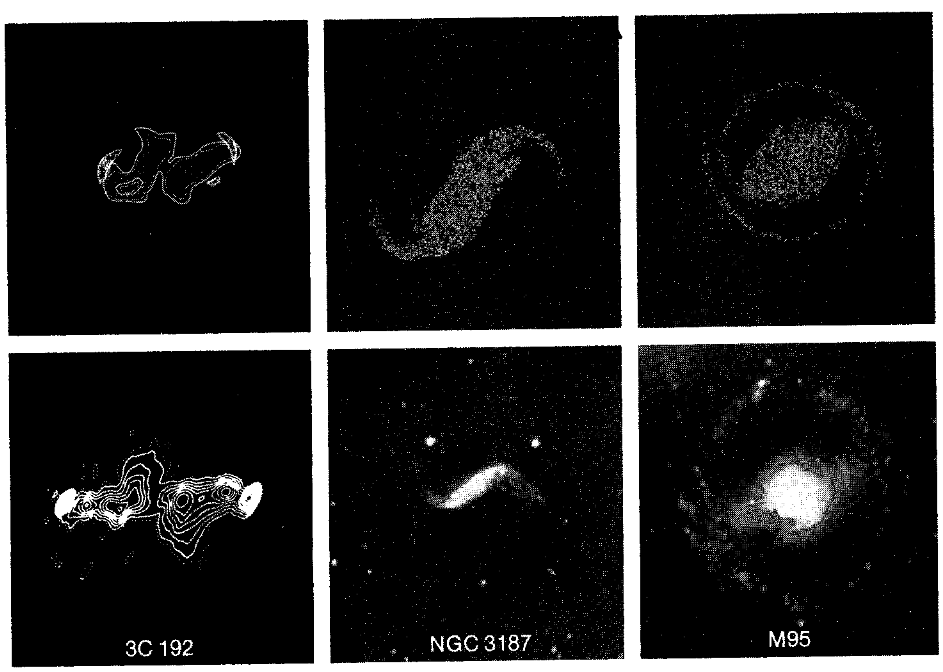
Birkeland had been trained as a mathematician and was able to cast the physics of his experiment into a set of differential equations. This work inspired one of his colleagues, Carl Störmer (who later gained fame as an auroral investigator in his own right), to carry out a tedious, step-by-step numerical integration of the equations in order to follow the path of each electron.

Birkeland relied not only on his terrella experiments but organized three expeditions to polar regions (1897, 1899-1900, and 1902-03) to study auroral currents and a later expedition to Egypt to study zodiacal light. He also established a worldwide network of "observatories" whose purpose was to measure the deflection of a compass needle when auroras occurred. From these data he was able to calculate and plot the vectors of electrical currents that flow in the ionosphere.

While his results were largely neglected until space probes were able to make *in situ* measurements of the ionosphere and magnetosphere, the advent of supercomputers has provided another affirmation of the Birkeland currents. They have now been studied on the most powerful computer ever assembled. This is at the Los Alamos National Laboratory in the form of four Cray-1's and two Cray-XMP's. Not unlike Galileo's telescope, this computational resource is unprecedented for providing insights and solutions to astrophysi-



The forces between two adjacent Birkeland currents, that is, electric currents aligned along magnetic field lines. (By historic convention, the current flow is taken to be opposite that of electrons, shown here in helical orbits about the field lines.) The parallel components of current (dark gray lines) are long-range attractive, while the counter-parallel azimuthal currents (light gray rings) are short-range repulsive. A third force, long-range electrostatic repulsion, is found if the electrons and ions are not present in equal numbers. These forces cause the currents to form sheets, filaments, or "magnetic ropes," and they can be found far from the source region. A projection of the current-induced magnetic fields is shown above the graph.



Time evolution (top, left to right) of two plasma clouds carrying Birkeland currents. As the axial current increases, the magnetic lines between currents produce an axial "betatron," an induction particle accelerator invented by Donald Kerst at the University of Illinois in the 1930's. The top left figure shows the magnetic-field energy contours produced by two interacting Birkeland currents (outer "hot spots") and, in between the currents, contours of the axial electric induction field produced by the magnetic fields as they change with time. These energies are responsible for synchrotron radiation observed in the simulations (*S&T:* July, 1983, page 19). Cross sections of the clouds several billion years later are shown in the figures at the top center and right. Note the similarities in the appearances of these simulations to those of the extragalactic objects illustrated at the bottom: a radio source at the left and the barred spiral galaxies at the center and right.

al phenomena, including the aurora. The lectron trajectory calculation that took Störmer and his students 18,000 hours to omplete requires but 6 seconds on a single Cray-1. A Birkeland auroral-current heet was recently simulated on a supercomputer; the resulting vortical-ray structure was in nearly perfect agreement with ll-sky photographs of an overhead auroral urtain (*S&T:* August, 1984, page 118).

Although the scientific attitude toward Birkeland's theory has changed to nearly otal acceptance, his cosmological views ave been little discussed. He almost certainly must have observed some of the phenomena recently "discovered" in 3-D computer simulations. As Birkeland filaments (see illustrations on the previous page) — or Birkeland current-carrying plasma clouds — interact, the resulting sequence of events causes the clouds to produce effects generally associated with well-known cosmic phenomena.

While gravity played little role in his experiments, and he could not have known about double radio galaxies nor measured synchrotron radiation, the radiation patterns formed in the simulations do match hose of radio galaxies. When gravity is ncluded, close agreements between simulated spiral galaxies and real ones are obtained (see illustration at right on the previous page). If correct, Birkeland's work ndicates that electromagnetic forces and encounters between galaxies are more important than previously thought.

Birkeland died in 1917 at age 49. Ironically, at the time of his death a working committee was in the process of nominating him for the Nobel Prize in physics. It is perhaps because of this unfortunate timing that his findings were so long neglected. Possibly the authoritative Chapman, dictating the course of electromagnetic research in the years that followed, found the concept of electric currents in "empty" space too fantastic an idea.

Carved in Norwegian on Birkeland's memorial is the inscription:

He combined atmospheric nitrogen
in his electromagnetic furnace
He investigated the nature of northern light,
the Sun's radiation
and the Earth's magnetic field.

REFERENCES

A biography of Birkeland, as well as the history of field-aligned currents in space, can be found in *Magnetospheric Currents,* T. A. Poterma, editor (American Geophysical Union, Washington, D. C., 1984), and *The Northern Light,* A. Brekke and A. Egeland (Springer-Verlag New York, 1983). Reviews of his investigations appear in *The Birkeland Symposium on Aurora and Magnetic Storms,* edited by A. Egeland and J. Holtet (Centre National de la Recherche Scientifique, Paris, 1968), pages 9, 13, 423, and 445.

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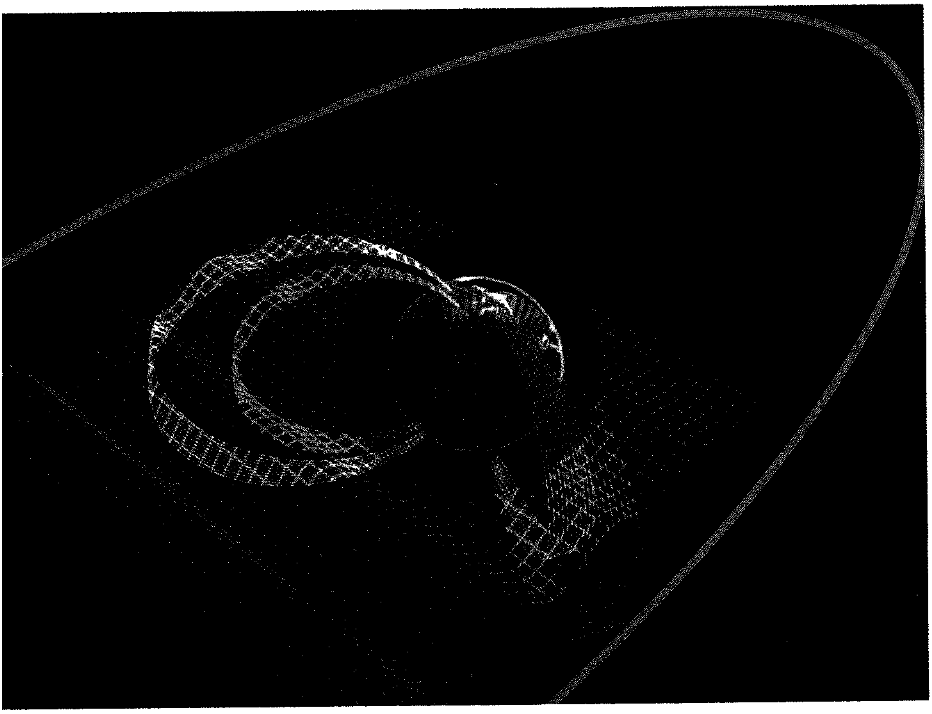

A voltage is generated close to the Earth's equatorial plane whenever a highly conducting plasma cloud from the Sun (orange) moves across the Earth's field lines (red in this computer simulation). The charged-particle flow (Birkeland currents), represented in green, is along the field lines toward the poles, then parallel to the ground, and finally back to the "generator" at a different latitude, along the blue-green lines.