Fifty years of magnetospheric physics at SSL: Instrument innovations and science discoveries

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Where was the field of magnetospheric physics 50 years ago?

Bierman observed 2 tails on comets > solar wind

Parker in 1958 published theory of solar wind

Parker, Sweet (1957,1958) published theory of reconnection to explain solar flares

Van Allen discovers radiation belt in 1958

Observations of electrons and x-rays in association with aurora by balloons and rockets

International Geophysical Year

Sputnick-1957

Creation of NASA- 1958
What was known about the aurora 50 years ago?

- Light emitted at ~100 km (60 miles) above the surface
- Light was emission from atmospheric constituents excited by collisions
- Rays were aligned along the geomagnetic field
- Strong aurora could disrupt telegraphs; associated with global scale magnetic perturbations
- Birkeland proposed currents along geomagnetic field
- Some scientists suggested connection to solar activity
Close interaction between theory and experiment leading to new understanding of physical processes.
Science at SSL enabled by new instrumentation and approach

- High time resolution particle distributions - Carlson
- 3d Electric field detectors from dc to high frequency with waveform capture (bursts) - Mozer
- Development of booms - Pankow
- Instrument data processing units and large burst memories - Harvey, Curtis
- Small satellites with integrated instrument payloads
Outline-aurora

Acceleration of auroral electrons

- S3-3 satellite - first satellite 3d measurement of dc field
- Rockets with high time resolution electric field and particle measurements
- FAST satellite
- Alfven wave carlson&mallinckrodt
- S3-3 - first to show definitively acceleration is low altitude and via parallel electric field; first to show existence of double layers and solitary waves (importance of time domain data)
- FAST - ‘3-regions’ - Alfvenic, downward, upward

small-scale structure and airplane photos
Motions and shapes of aurora

Museum of Time
Lapland aurora II
graphic: K.Akasofu; http://asahi-classroom.gi.alaska.edu/magfield01.htm
What process accelerates auroral electrons and where does it occur?

Quasi-static electric field acceleration

Wave acceleration
Rockets observed magnetic field-aligned mono-energetic peak in the electron distribution above aurora [McIlwain, 1960; Evans, 1965]

How to explain these observations?

A quasi-static parallel electric field

SSL rockets observe parallel electric field in association with strong aurora (Kelley, Mozer and Fahleson, 1971)
Electric fields parallel to the background magnetic field can’t occur in a collisionless plasma. Electrons are too mobile and will rapidly move to short out any field.

Experimental and theoretical research at SSL have elucidated physics of parallel electric fields.
Electric field detectors

balloons

rockets

satellites
S3-3, first satellite with 3d electric field detector, discovers electric field structures that accelerate auroral particles.

Interpretation of measurements of electric fields and particles

S3-3 satellite observed upward ion beams (O+, H+)
[Shelley et al., 1976]


Discovered that acceleration occurs at low altitudes (~2000-6000 km altitude)

Showed for first time that acceleration occurs via quasi-static electric fields parallel to the earth’s magnetic field
S3-3: First observations of double layers and solitary waves

Evidence for importance of microphysics, high time resolution measurements and electric field waveforms

Instrument innovations: very high time resolution particle distributions

Fig. 1 A comparison of normal and symmetrical quadrisphere geometries. With normal quadrisphere, the response varies with polar angle. Symmetrical analyzer has cylindrical symmetry with complete 360° field of view. Typical trajectories illustrate focusing characteristics.
Rockets using high time resolution particles and fields
Rockets observe high time resolution variations (‘flickering’ at \~10 Hz) in aurora: evidence for wave processes. Theoretical model matches observations, showing electrons accelerated by ion cyclotron waves.

Innovation-small, integrated satellites: FAST
Relationship between individual narrow arc, electrons, currents and electric fields.
measurement of $E_{||}$ from Ergun et al., 2002

adapted from Mozer and Hull

“quasi-steady”

Measurement of $E_{||}$
FAST observes directly electron acceleration by sw

Electron modulation used to measure speed of ion solitary waves and identify mode

‘Black’ Aurora

For the REAL black aurora story, see

FAST explores physics of downward current region

Acceleration of electrons upward in quasi-static parallel electric field- mirror image to upward ions in upward current region

McFadden et al., 1999
FAST explores physics of downward current region

‘Inverse’ aurora with interesting microphysics due to interaction of cold, dense ionosphere and hot tenuous plasma sheet.
First observations of electron holes.
First evidence for strong double layers


Time dependent wave processes: Alfven waves

Importance of shear wave ‘conductivity’ compared to ionospheric Pederson conductivity
Electron acceleration by kinetic/inertial Alfven waves

- Kinetic Alfven waves propagate near Alfven velocity
- Have E field parallel to B
- Accelerate along B due to velocity gradient
- “Snow plowing” electrons along B
- Accelerate large fraction of electrons to several keV—large energy flux (damping of waves)
- Several kilometer perp. scale at 100 km alt (thin arcs)
FAST observes acceleration of electrons in Alfvén waves: Agreement between data and simulations


FAST ‘3 Regions of auroral acceleration’
What powers the auroral acceleration?

What causes the dramatic variations in auroral substorms?
Reconnection changes topology of magnetic field

from Baumjohann and Treumann, 1997

Reconnection is an energy conversion process
- Converts magnetic energy to rapid flow and heat
- Powers solar flares, storms, auroral substorms
Evidence that reconnection occurs

• Early satellite results
• Balloon electric fields
• Rocket-cusp
• ISEE

Microphysics of reconnection

• Polar - 3d electric field
• Cluster
• THEMIS - 3d electric field


Occurrence of reconnection was well-established by the 1980s but many critical questions remained.

What controls the speed of reconnection process? How fast and how efficient is the energy conversion?
How are ions and electrons ‘decoupled’ from the magnetic field?
Over what scale-sizes do processes occur?
Motion of charged particle in electric and magnetic field

The simplest picture of magnetized plasmas is a fluid one (MHD). If there is no resistivity, the magnetic flux through a given fluid element stays fixed. This is called the ‘frozen-in condition’ - \( \mathbf{E} + \mathbf{v} \times \mathbf{B} = 0 \)

Kivelson and Russell, 1995

http://www.physics.ucla.edu/plasma-exp/Beam/
Speed of reconnection

Petschek, 1964

\[ R_{SP} = R_m^{-1/2} \propto \sigma^{-1/2} \]

\[ R_P = \pi / (8 \ln R_m) \propto 1 / \ln \sigma \]

Size and shape of reconnection region and effective conductivity are keys to understanding.
Breaking the frozen-in condition

\[ E + v \times B = \eta j + \frac{1}{ne} j \times B - \frac{1}{ne} \nabla \cdot P_e + \frac{m_e}{ne^2} \frac{\partial j}{\partial t} \]

- Resistive: \( 1/(v\mu_0 \sigma) \)
- Hall: \( c/\omega_{pi} \)
- Pressure: \( \rho_{i,s} \)
- Electron Inertia: \( c/\omega_{pe} \)
First observation of Hall magnetic field signature

Decoupling of ions and electrons explicitly measured


Ions were observed not to ExB drift over scales of several ion skin depths.

For electrons the scales was smaller.
Parallel electric fields have widths in normal direction of about one electron skin depth and they extend over at least four ion skin depths. Energy conversion over similar scales.

Electric field supported by inertia and electron pressure

Strong evidence for multiple regions of electron de-coupling

In situ evidence that reconnection is a continuous process when the interplanetary magnetic field is constant. Cluster data showed jets consistent with theory for ~2 hours.


Similar results in optical data from IMAGE:

Fig. 1. Projections of THEMIS probes in X-Z_GSM plane along with representative field lines and neutral sheet location in GSM coordinates at 04:45 UT on 26 February 2008. Times refer to the time delays in Table 1.
What will the next 50 years bring?

• Continued innovation in instrument design
• Continued improvements in spacecraft design and operations
• Exciting new discoveries in the physics of the magnetosphere
Angström, in 1866

- Red oxygen -6300 Å -~100s
- Yellow/green 5577 Å oxygen -~3/4s

⇒ Not identifiable in laboratory until 1923 because meta-stable state
What do these phenomena have in common?

*Radio emission due to electron cyclotron maser instability*

- Extremely high brightness temperature.
- Nearly 100% circularly polarized.
- Narrow frequency band.
- Strong variability.

Energy source is electric field parallel to background magnetic field, which accelerates electrons.
Norse: Bridge, Bifrost, connected Earth and Åsgard, home of gods.

Eskimo: Torches of spirits leading souls of violent or voluntary deaths on path to paradise. Can send messages to dead by whispering to them. Aurora are departed souls, playing ball with walrus skull.

Menomini: Light of torches used by friendly giants to spear fish at night.

Maori: Fire lighted by ancestors whose canoes drifted far south.

Sami: Light of dawn shining at night. Supernatural powers to resolve conflicts.

Norse: Bridge, Bifrost, connected Earth and Åsgard, home of gods.
S3-3 -first satellite with 3d electric field detector

Discovered that acceleration occurs at low altitudes (~2000-6000 km altitude)

Showed definitively that acceleration occurs via quasi-static electric fields parallel to the earth’s magnetic field

Fig. 1. Geometry of the S3-3 satellite and of the magnetic coordinate system in which field-aligned current and electric field data are presented.

Fig. 7. Meridional plane view of a possible equipotential structure associated with paired electrostatic shocks.
FIG. 3 (color). Cluster-1 crossing of a reconnection exhaust in the vicinity of an X-line and the comparison between the observed and simulated plasma and field profiles. (a) Magnetic field, (b) ion bulk flow, (c) ion density, (d) electric field components in the X-line frame, (e) electric field in the spacecraft frame. The X-line frame was constructed from the spacecraft frame by a translation of $v_L = -100$ km/s, $v_M = -127$ km/s, and $v_N = -40$ km/s based on the ambient magnetosheath flow. The spin-axis component of the electric field $E_z$ was constructed using the $\mathbf{E} \cdot \mathbf{B} = 0$ assumption (when the GSE fields satisfy $|B_{Lz}/B| < 2$ and $|B_z| > 2$ to prevent small errors in the measured $E_z$ from being amplified by small $B_z$ to produce large errors in $E_z$). Panels (f)-(i) show the corresponding plasma and fields parameters from the simulation along the cut shown in Fig. 1.
Auroral parallel potential drops: How are they distributed?

- **Spatial dependence**
  - Distributed uniformly over large scales
  - Confined to narrow layers
  - Some combination

- **Time dependence**
  - Steady-state (or quasi-steady)
  - Time dependent

We still don’t know all the answers; research from FAST, Polar and Cluster continues to provide new insights.
adapted from Mozer and Hull
Auroral substorm

S. Mende