Challenges in high-latitude geospace science
Solar Wind “Input” to SW-M-I-T Coupled System (IMF southward)
I-T “Response” to SW-M-I-T Coupled System (for IMF Southward)
Northward IMF: SA Arcs, Theta Aurora Rare
Only after hours, Magnetosphere Reconfigures
(ISEE) Lobe connection to Theta Aurora?

(Huang 1987)
Cartoon of Polar Cap: (left) $B_z < 0$, (right) $B_z > 0$
Left: Hypothesized life-cycle of patches; Right PC arcs
Carlson, 1994
However, this is tracking actual data
Daylight/noon top, thru terminator, darkness bottom
Bright diffuse areas are PC “patches” from actual TEC receiver data
Zhang et al, 2013
Patch Lifecycle seen in actual TEC data
Daylight/noon top, (terminator middle) darkness bottom
Red = 17 TEC units; PC “patches” tracked by black circle

Zhang et al, 2013
(Return) Blob “the second time around”
Dual Beam Ne, Te, Ti, and Vi vectors!
(Moen et al, 2006)
“Blob” returning to noon: segmented thru Cusp
CUTLASS HF backscatter-power IMAGE 07:00-07:45 UT
Matches dual beam EISCAT ISR electron density “islands”
Moen et al, 2006
(Enter) IMF southward region Cusp
[Flow Shear $\sim 200$ km x $1500+$ km ]

IMF $B_z < 0$, $B_y > 0$
Dramatic Tongue of ionization
(what is granularity within tongue envelope?)
(Foster et al, 2005)
PULSED MAGNETIC RECONNECTION A-B
Merging gap a-b, noon top, --- Ne contour
(Lockwood and Carlson, 1992)
Typical Patch is Oval, antisunward
Most of time see flow jets and segments
(Carlson, 1993)
Left: Ne 71-80° latitude (red ~daytime Ne), 2 min frames: top fossil patches, mid birth of patch
Right: ASIP 777.4 showing two PMAFs (grey), Carlson et al. 2006
Coincides with Flow shear, PMF, structure

Carlson et al, 2008
(Cross)Patches Characterize IMF southward

Why called PC “Patch” when discovered

(Buchau and Weber, 1981)
Sun Aligned Arcs Characterize Northward IMF (point towards thw sun)
PS Arcs characterize IMF Northward
Within minutes, much weaker than Theta Aurora
Currents are in rest frame of the Neutrals
Sun Aligned Arc
Thermal/energy/electro dynamics

[Diagram showing altitude and distance with annotations for Particle Energy, Poynting flux, enhanced $T_e$, enhanced $T_i$, Birkeland Currents, Pedersen Currents, Plasma drift, Hall Currents]
Sondrestrom derivation of thermal and energy balance terms
Poynting, Joule, Ti->Tn, Particle, $\Sigma_{p}$
(Exit) Patches Exiting PC (recon?)

Trajectory, Morphology. Physics of patch exit

Moen et al, 2007

Occurrence rate of polar cap patches

Eight winters (1997-2005) of MSP data from Ny-Ålesund have been analyzed
43 nights, 333 events
About 60% of the patches exit the polar cap from 22-01 MLT, but patches were observed in the entire MLT range from 18:00-05:00.
IRI can benefit greatly where data-starved
(Climate vs. Weather) Cusp $N_m F_2$ Peaks ~noon & midnight
Several data starved parameters could benefit
Moen et al, 2008
PC in “Two States”: IMF South, North Detect in cusp in 2 min, flow channel in 5
Polar Cap F-Region Structures: TWO states
Left: IMF Northward, velocity shear driven
Right: IMF Southward, late time Gradient drift (Carlson, 2003)
$\delta E/(\delta N_{e}/N_{e})$: observed in Polar Cap

Velocity shear 10x Gradient drift
Solar cycle variation of PC scintillation
Can disrupts Communications and Navigation
Almost an on/off 6-year switch

(Basu et al. 1988)
DE Patch Frequency (IMF south)
Strong UT winter dependence

(Coley and Heelis 1998, Basu and Valladares 1999)
Neutral Gas $i$-$n$ Momentum (no gradients)

$$\frac{dV_n}{dt} = \left(\frac{\rho_i}{\rho_n}\right) v_{in} \left(V_i - V_n\right)$$

$\text{foF2: } 9 \text{ MHz} \sim 0.5 \text{ hr}; \ 3 \text{ MHz} \sim 5 \text{ hrs}$
Vn up to speed with Vi (Climate)
Vi changing too fast for Vn to keep up
(Weather) Note strong frictional heating
Now What can we Measure: Global ISRs
RISR-N without RISR-S
RISR-N+S Sub-Cusp Through Polar Cap
Huge Advance!
E-POP satellite

- **Orbit**: 325 x 1500 km, 80.99° inclination
- **Orbital Period**: 103 minutes (14 orbits per day)
- **Projected Lifetime**: 2 years
- **Science Instruments**: VHF/UHF transmitter (CER), VLF/HF receiver (RRI), auroral imagers (2) (FAI), GPS receivers (5) (GAP), ion detector (IRM), electron detector (SEI), neutral particle detector (NMS), magnetometers (2) (MGF)
DMSP 4 consecutive passes
SuperDARN Northern Hemisphere
All Sky Imaging Photometers
630 nm MSP scan NYA Svalbard
As patches exit PC near midnight
(Magnetic Reconnection Signature?)
Moen et al, 2007
Open- to Closed-B nightside flow jets, Poleward boundary Intensifications (PBI)

Earthward/equatorward mesoscale plasma flows

Lyons et al, 2011
PULSED MAGNETIC RECONNECTION A-B
Merging gap a-b, noon top, --- Ne contour

(Lockwood and Carlson, 1992)

STATIONARY MERGING GAP $\rightarrow$ TONGUE

MIGRATING MERGING GAP $\rightarrow$ PATCHES
When magnitude of IMF $B_y$ is large, get strongest flow in magnetic tension direction.

(Carlson 2003)
Must smooth SuperDARN for global picture
(Climate) \( V_i \sim 1/\text{km/s} \) typical high

Foster et al, 2005)
Must not smooth for mesoscale Plasma (Weather) Flow Shear: SuperDARN
Does it matter?
It did to an 8 year old unsolved problem
Density/Drag Doubling over the Cusp

• Why Thermospheric Density/Drag Should Double Over the Cusp
Back to Basics (Equivalent by Math)

Altitude dependent Energy Deposition Rate \( \Rightarrow \delta T_n(h)/\delta t \)

Three Equivalent Formulas

Altitude Profile of Current/Joule Heating

\[
j \cdot E; \quad \rho E^2 \quad \text{W/m}^3
\]

Altitude Profile of \textbf{Ion Frictional Drag} Heating

\[
\frac{E_n}{t} = (n_i \cdot m_i \cdot \text{in})(V_i - V_n)^2
\]

Ti Surrogate Altitude Profile of Ion Frictional Drag Heating

\[
\frac{E_n}{t} = \frac{3k_B}{m_n} \quad (n_i \cdot m_i \cdot \text{in})(T_i - T_n)
\]
Equivalence vs. Causality

- One can derive equivalence of thermospheric heating rate from: $J \cdot E, V_i - V_n, T_i - T_n$ [Theyer & Semeter, 2004]

- For causality, understanding the MIT coupled system most directly from mechanical frictional drag ($E$ is a consequence of flow, not a cause) [Pakrer 1996, Vasyliunas 2001, Strangeway 2012]

- For solar wind energy input [vs. thermosphere energy sink], currents relate best to causality
Joule dissipation and frictional heating in the collisional ionosphere
R J. Strangeway (JGR 2012)

• Investigate the role of frictional heating

• most of the **Joule dissipation in the neutral frame**, results in heating mainly by initially increasing the ion fluid temperature relative to the neutrals, while the neutral atmosphere temperature increases much more slowly.

• Energy input from the solar wind to the M-I-T system is inherently currents (vs. frictional I-T)
Altitude Profile of **Ion Frictional Drag** Heating

\[
\frac{E_n}{t} = (n_i \ m_i \ \text{in}) (V_i - V_n)^2
\]

Square Law Dependent on ion velocity shear
[i.e. Plasma Flow Jets]
Linearly Dependent on Electron Density Profile
Plasma Flow Shear: EISCAT Radar
Plasma Flow Shear: DMSP (PMAF)
Climatological energy deposition rates compared to those from Space Weather

(Carlson, 2012 using Thayer and Semeter 2004)
Small Heat in at 200 km Compounds!

10% at 200 km $\rightarrow$ 100% more drag at 400 km

$n\ (O) \ \text{cm}^{-3}$

![Graph showing the relationship between altitude (km) and log of oxygen density (cm$^{-3}$).](image-url)
Poynting’s theorem: ionospheric application
A. D. Richmond (JGR 2010)

- Poynting vector from spacecraft $\delta E \times \delta B$ cross product, used to estimate the field line-integrated EM energy dissipation in the ionosphere below:
  - the downward perturbation Poynting vector can underestimate the EM energy dissipation in ionospheric regions of high Pedersen conductance,
  - and can significantly overestimate the dissipation in regions of low conductance.
A NEED Polar F-layer model-observation comparisons: a neutral wind surprise

Sojka et al, 2005

• Abstract. Physics-based ionospheric models, are usually only compared with observations over 1-2 day events or climatological averages.

• Using month-long ESR observations, the daily weather, day-to-day variability, and month-long climatology can be simultaneously addressed to identify modeling shortcomings and successes.

• Since for this study the TDIM is driven by climatological representations of the magnetospheric convection, auroral oval, neutral atmosphere, and neutral winds, whose inputs are solar and geomagnetic indices, it is not surprising that the daily weather cannot be reproduced.

• Unexpectedly the horizontal neutral wind has come to the forefront as a decisive model input parameter in matching the diurnal morphology of density structuring seen in the observations.

• Zero Neutral wind beat any other neutral wind model input
Patch structure 1st by Shear, not Grad Drift
Gradient drift can’t respond this fast, dominates in central PC
Carlson et al, 2008
Ion Upflows MLT noon +/- 2 hours
Top Ti, Mid Vi, Bottom PMAFs (EISAT)

Moen et al, 2004
• How does solar wind-magnetotail-ionosphere coupling affect the structure and composition of the polar ionosphere?

PC in "Two States": IMF South, North
Detect in cusp in 2 min, flow channel in 5
• What are the effects on the neutral atmosphere, and what is the range of influence of these disturbances?

**Back to Basics**

*Altitude dependent Energy Deposition Rate* \(\frac{\delta T}{\delta \tau}\)

*Three Equivalent Formulas*

**Altitude Profile of Current/Joule Heating**

\[ j \cdot E' \cdot \sigma_j E^{12} \mu W/m^3 \]

**Altitude Profile of Ion Frictional Drag Heating**

\[ \frac{\partial E_n}{\partial t} = \sum (n_i \cdot m_i \cdot V^i) \cdot \frac{V_i - V^i}{\lambda} \]

**Ti Surrogate Altitude Profile of Ion Frictional Drag Heating**

\[ \frac{\partial E_\perp}{\partial t} = \frac{3k_B}{m_i} \sum (n_i \cdot m_i \cdot V_\perp) \cdot (T_i - T_\perp) \]

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• What governs the internal structure and RF propagation characteristics of plasma patches?

**\(\delta E/(\delta Ne/Ne)\): observed in Polar Cap**

**Velocity shear 10x Gradient drift**
- How do these processes affect plasma outflow and its impact on magnetospheric configuration?

Ion Upflows MLT noon +/- 2 hours
Top Ti, Mid Vi, Bottom PMAFs (EISAT)

PHISR, RISR-N/S, Sondrestronfjord

When is the role of pulsed magnetic reconnection in unifying our base of understanding at the cross-roads of these and more?

PULSED MAGNETIC RECONNECTION A-B
Merging gap a-b, noon top, --- Ne contour

STATIONARY MERGING GAP ➔ TONGUE

MIGRATING MERGING GAP ➔ PATCHES
Newly reconnected flux tube paths

(Lockwood et al, 1993)
Small scale Irreg onset time is minutes

Moen et al, 2000