Systematic numerical analysis of high-altitude photoelectrons at Mars

Michael Liemohn, Yingjuan Ma

Center for Planetary Science

AOSS Department, University of Michigan, Ann Arbor, MI USA

Also starring:

R. Frahm SwRI, San Antonio, TX USA

J. U. Kozyra, A. F. Nagy U-Michigan

D. Winningham, J. Sharber SwRI

S. Barabash Swedish Institute of Physics, Kiruna, Sweden

And the ASPERA-3 Team

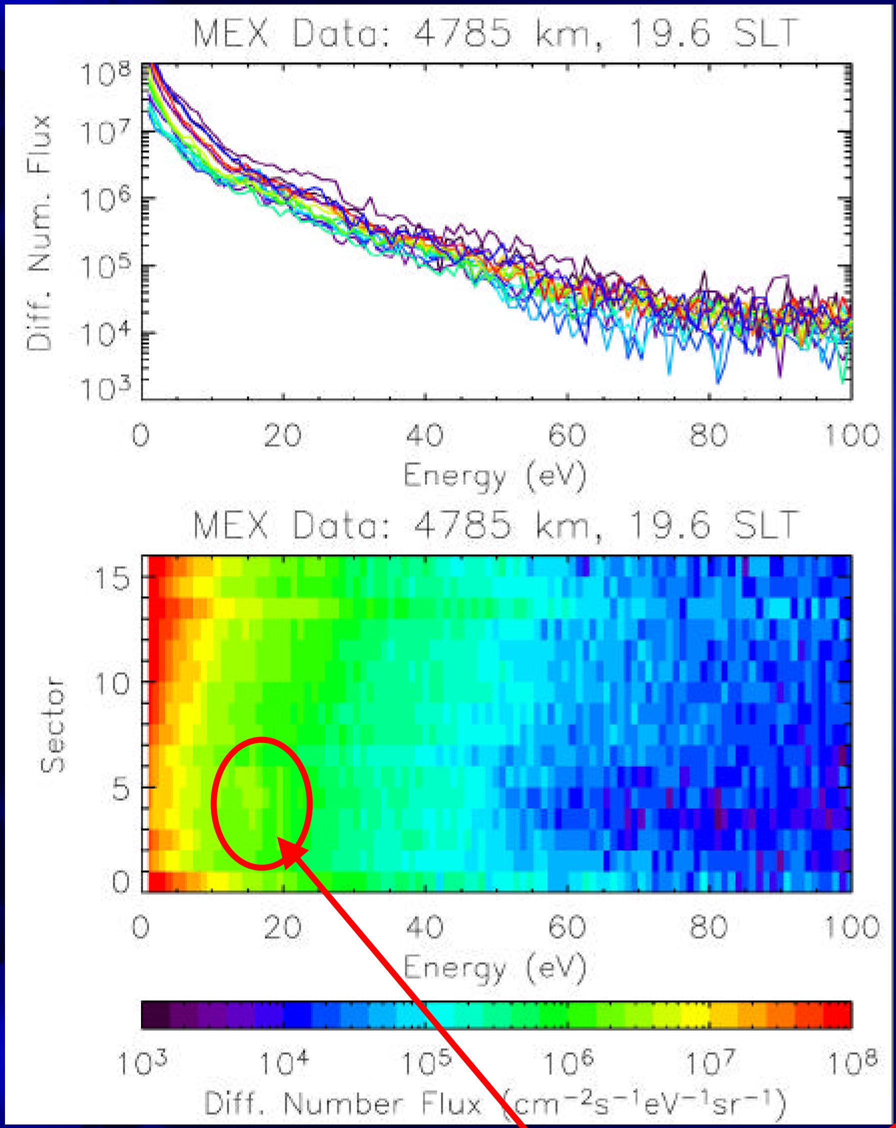
The Issue

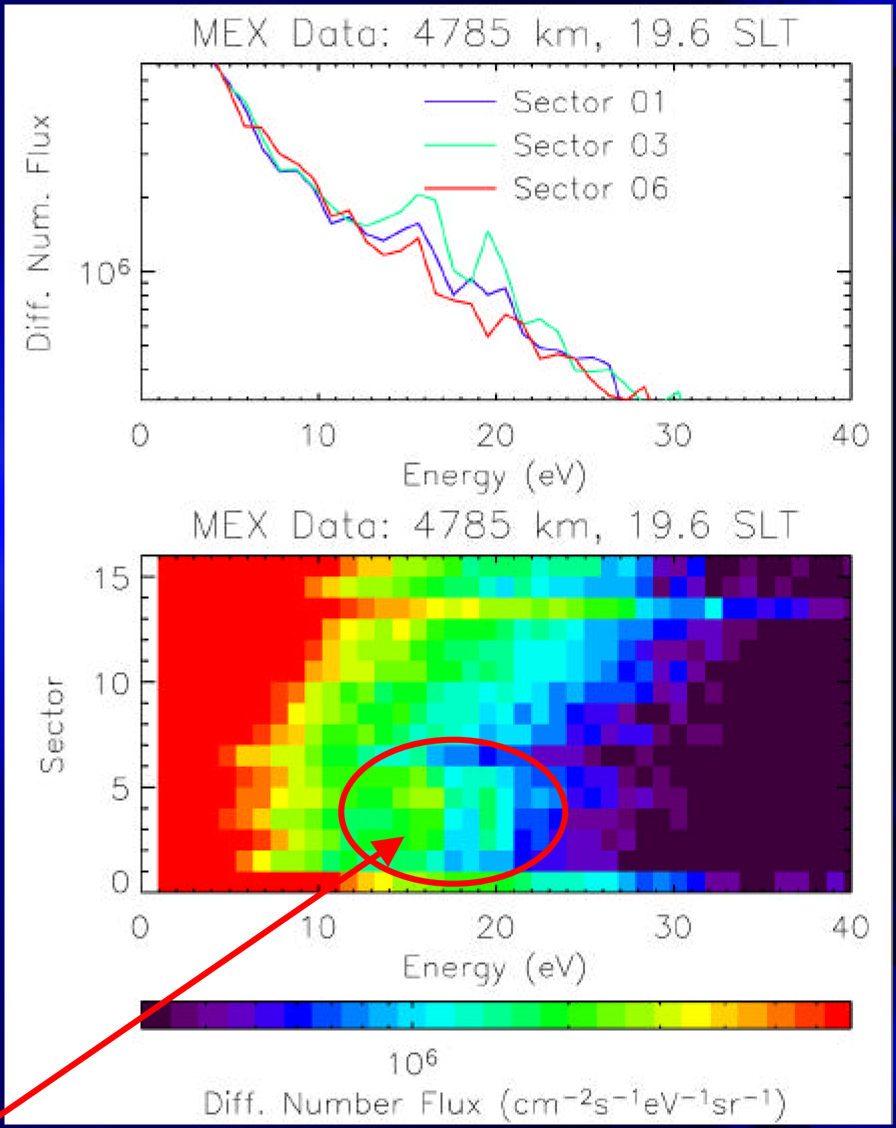
- Atmospheric photoelectrons are seen way above the ionosphere (by ASPERA-3 on Mars Express)
  - Seen up to 10,000 km altitude (MEX apoapsis)
  - Seen in the evening sector (sampling bias?)
  - Seen sporadically or continuously on many orbits
  - Seen streaming away from Sun direction
- The Question:
  - What can modeling say about the existence, origin, transport, and features of these electrons?
  - *In particular*: when and where can we expect to see atmospheric photoelectrons at high altitudes?

Observed Sector Width is Narrow

All sectors, full dynamic range

A few sectors, limited dynamic range

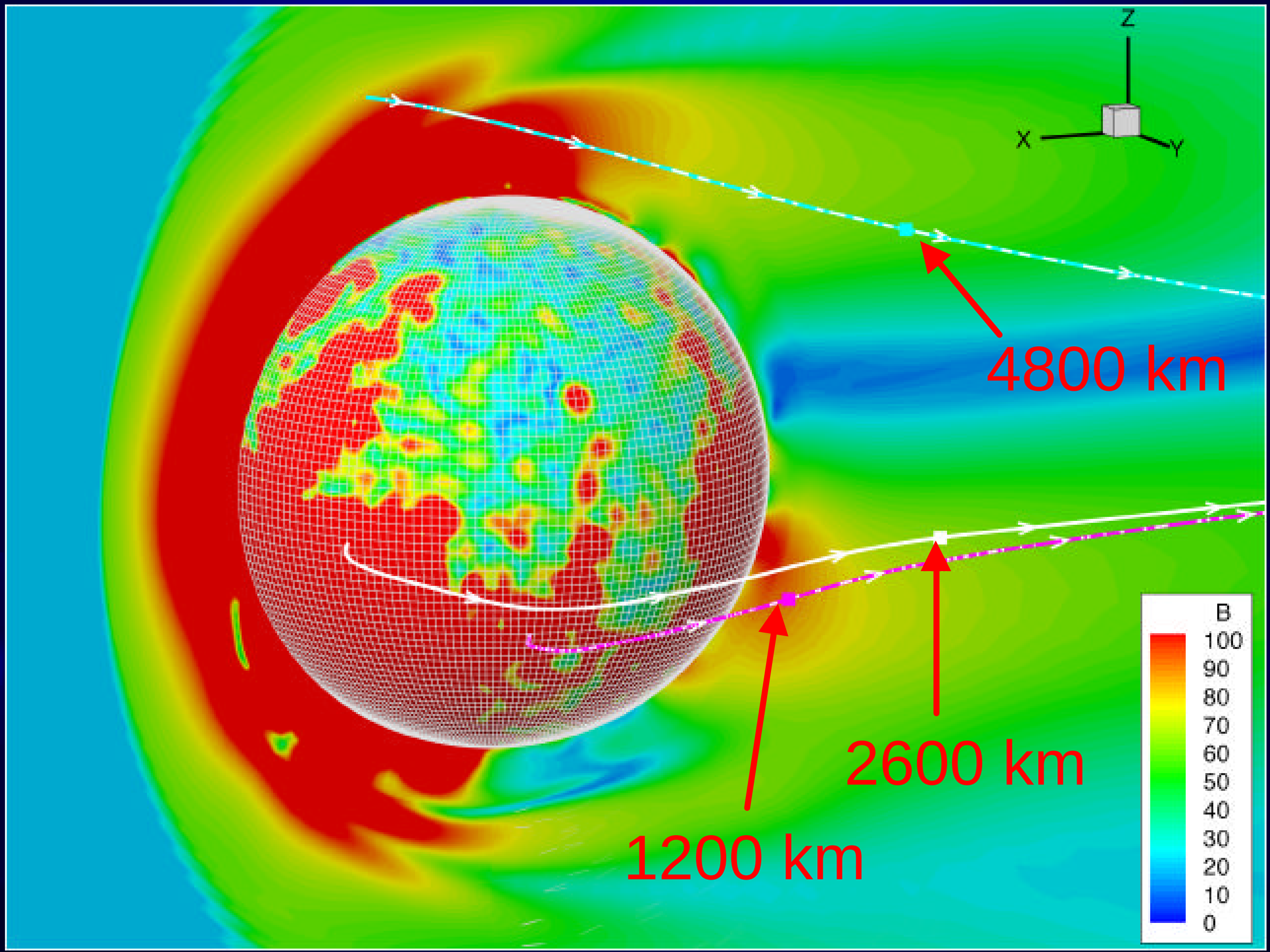




Atmospheric Photoelectrons…only seen in a few sectors

Case Study Analysis: Magnetic Field Line Tracing

- Three selected field lines connected to photoelectron observation locations
  - Two of the three show connection to Mars!



Case Study Analysis: Data-Model Comparisons

Data Facts for the Three Example Cases

Case	Altitude km	SLT h	Latitude Deg.	PE data # of sectors	PE data Peak sector
1	1200	20.4	-16	3	3
2	2600	21.1	3	4	3
3	4800	19.6	29	5	4

Model Facts for the Three Example Cases

Case	Bx nT	By nT	Bz nT	|B| nT	Sun-B Angle Deg.	Source cone Deg.	Sim. PA extent (@ 23 eV) Deg.
1	-11.4	0.83	2.6	11.7	-4	27	30
2	-9.8	0.29	0.46	9.8	-2	18	40
3	-4.0	3.9	-0.84	5.7	-44	40	47

Data-Model Comparisons for the Three Example Cases

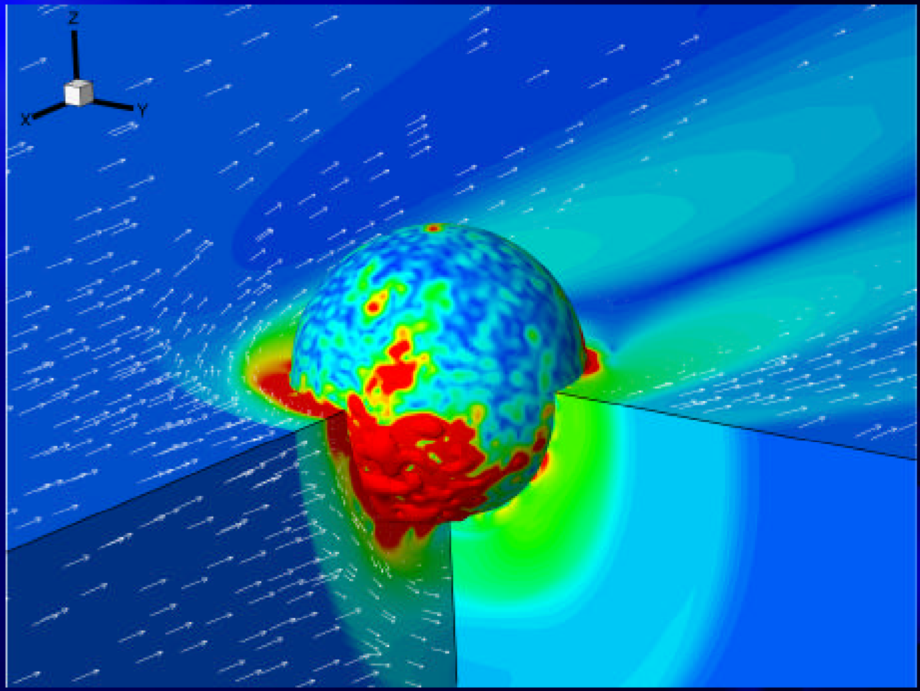
Case	ELS-B Angle Deg.	Obs. PA extent Deg.	Obs. PE PA extent Deg.	Obs. PE Peak Offset Deg.
1	77	13-167	47	0
2	87	3-177	48	0
3	81	9-171	66	-23

What to do next?

- Extract many field lines from the MHD simulation
  - See when and where there is magnetic connectivity to the ionosphere
  - Interpret the various quantities about the closest approach and high-altitude locations along B lines
- Parameter analysis:
  - Determine how this varies with subsolar longitude
  - Determine how this varies with solar wind inputs

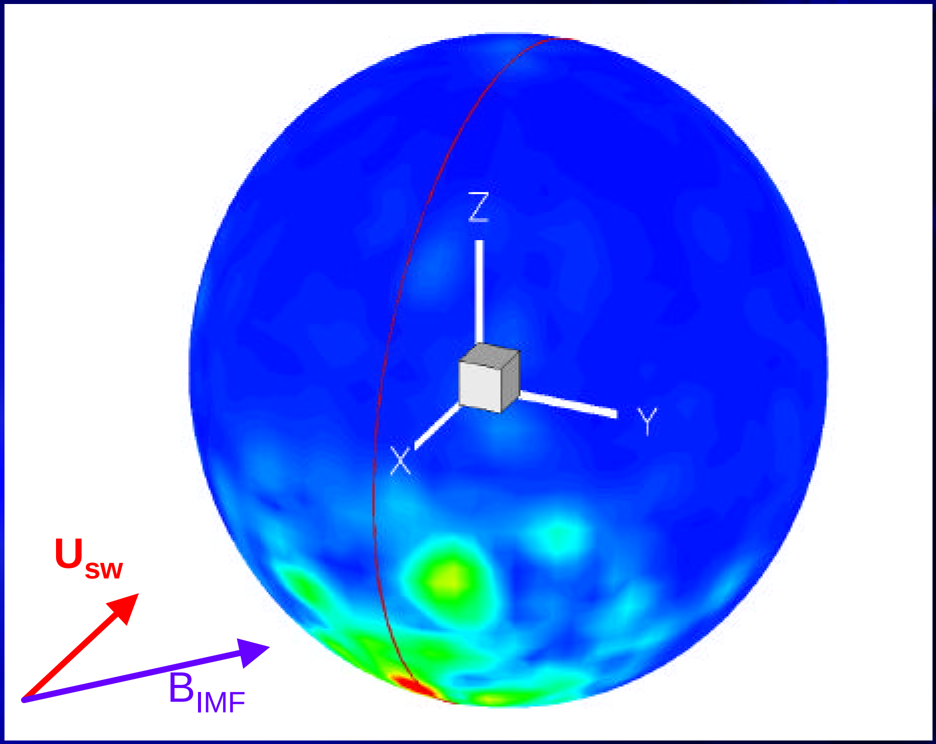
The Ma et al. MHD Model

- Solves the dimensionless conservative form of the ideal MHD equations
  - Separate mass densities for H^+, O_2^+, O^+ and CO_2^+
  - Single velocity and temperature
- Spherical Coordinates:
  - Radial resolution
    - 10 km to 600 km
  - Angular resolution
    - 1.875 to 3.750°
  - Boundaries
    - 100 km to x=[+8,-24] R_M
    - y,z=[-16,+16] R_M



MHD Simulation Details

- Solar wind parameters
  - $n_{sw} = 4\ cm^{-3}$; Usw = 400 km/s
  - B_{IMF} in the X-Y plane (56° angle with the SW flow) and |B|= 3 nT
  - $T_e = 3x10^5$ K, $T_i = 5x10^4$ K
- Inner boundary conditions
  - $[O_2^+]$, $[O^+]$, and $[CO_2^+]$ are in photochemical equilibrium (solar minimum photoionzation)
  - Plasma temperature is assumed to be 400 K and pressure is set accordingly
  - $B=B_0$, where B_0 is the crustal field [Arkani-Hamed, 2001]



<u>Two simulations conducted:</u>

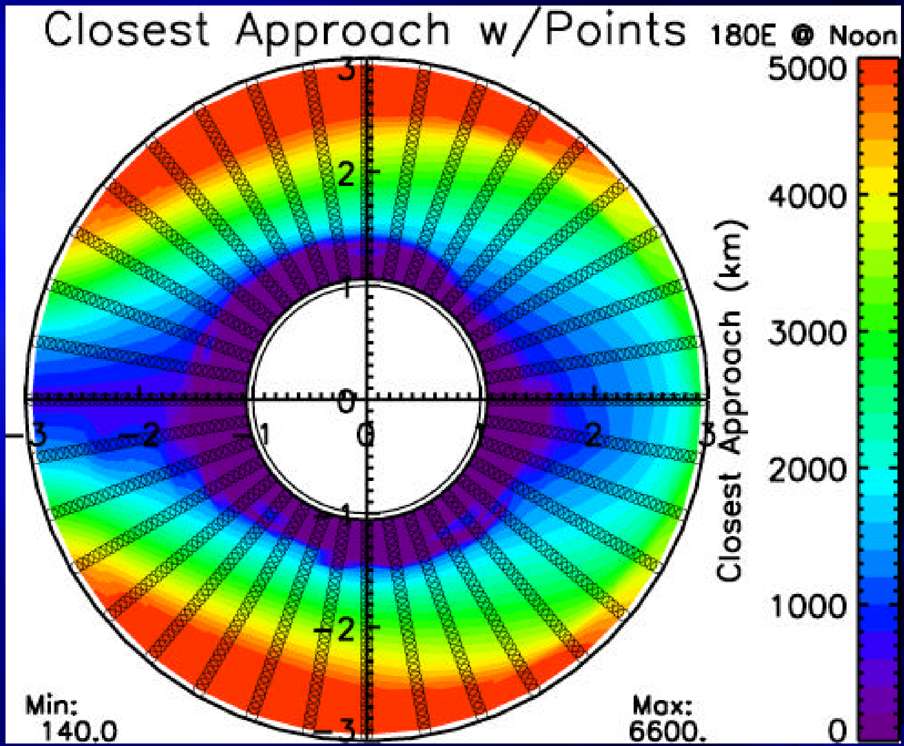
- 180E @ noon
- 0E @ noon

Field Line Extraction

- 1188 field lines pulled from each of the 2 simulations
  - Starting points in the terminator plane (X=0)
  - 33 altitudes: from 200 to 6600 km every 200 km
  - 36 latitudes: every 10° around the dawn-dusk plane
  - Track the field line in each direction from these points
  - 20 km step size along the field lines
  - Stop when it reaches the outer or inner simulation boundary
  - Save location and magnetic field vector information
- Other quantities computed from these values:
  - Closest approach altitude, LT, latitude, $\underline{B}$, B
  - Terminator plane properties, TP/CA B-field ratios
  - Determine which field lines pass through other X=a planes

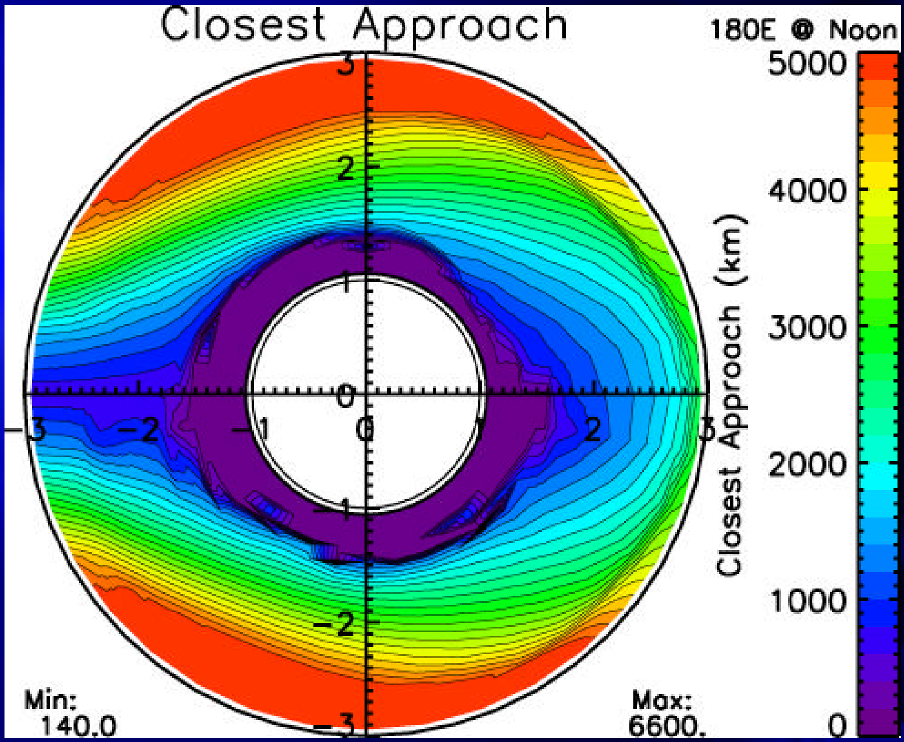
Field Line Analysis: Plot Format

- Terminator plane (X=0)
  - Distances to 3 R_M
  - Colorscale shows values for some quantity
  - Min/max listed below
- Density of extraction
  - Open circles show each extracted point in TP
  - 33 alts: [200 km, 6600 km]
  - 36 degs: [0°, 350°] in plane



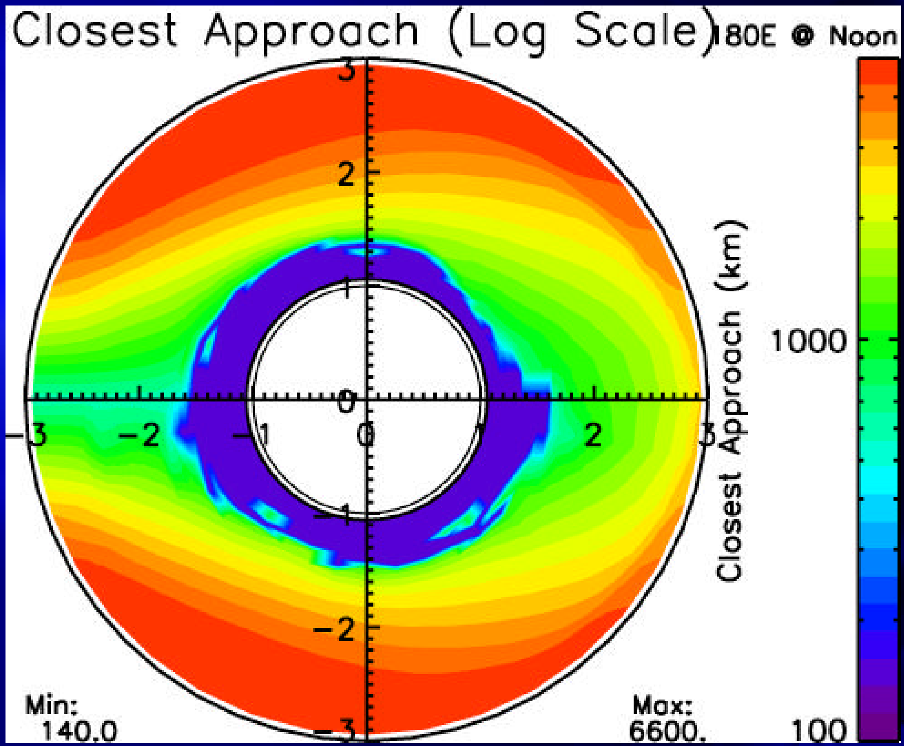
Closest Approach: 180E @ Noon

- Closest approach values
  - CA altitude for the line from that TP location
  - Minimum CA = 140 km
    - Ionospheric peak altitude
    - Note: R_{body} @ 100 km
- Asymmetric in Y
  - Parker spiral IMF (B_z=0)
- Some connected to ionosphere!
  - Ring out to 1000-2000 km altitude that hits 140 km

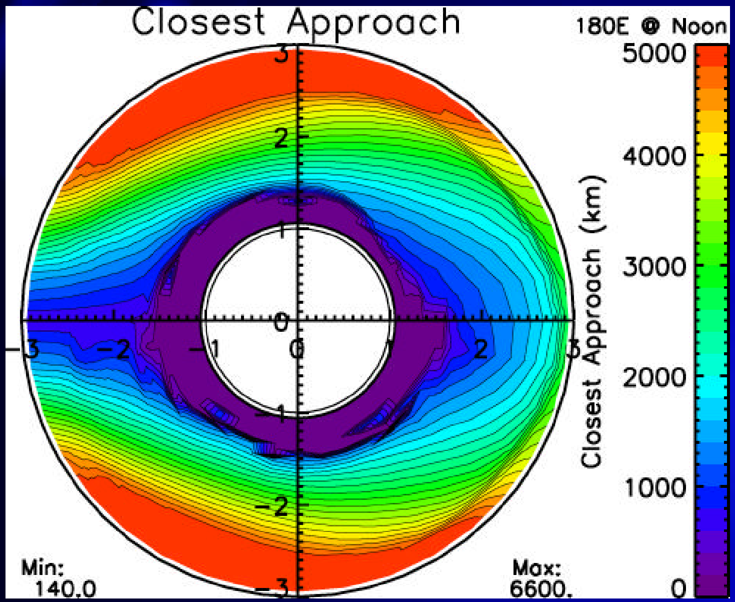


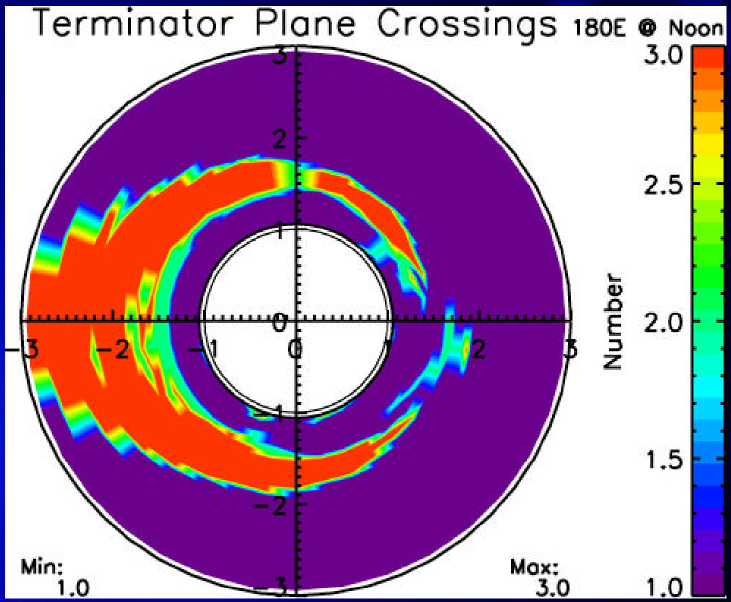
Closest Approach: Log Scale

- Let's plot it on a log scale
  - Highlights lower altitude CA values
- Big step between 140 and ~500 km CA altitude
  - Why?
    - MHD result has the magnetic pileup peak below 200 km
    - Tracing gets tough at these altitudes, resolution issues
- High-alts along -Y axis:
  - 500-600 km CA altitude



Terminator Plane Crossings

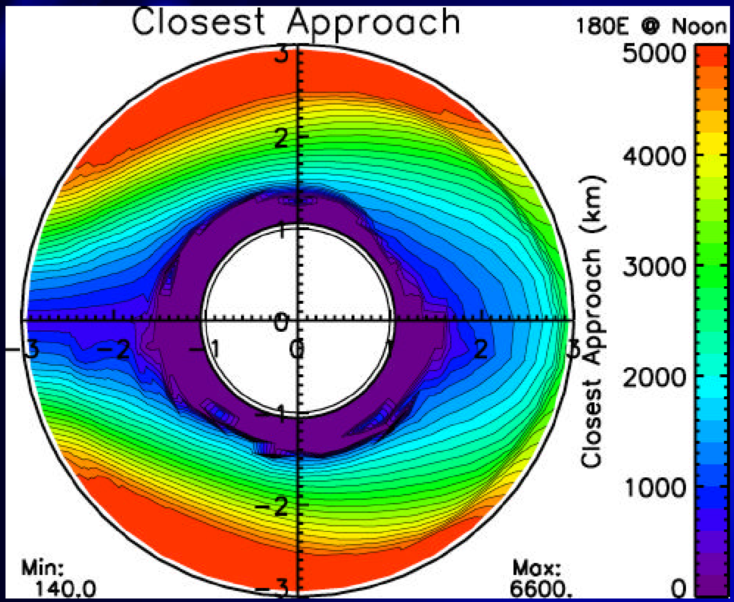




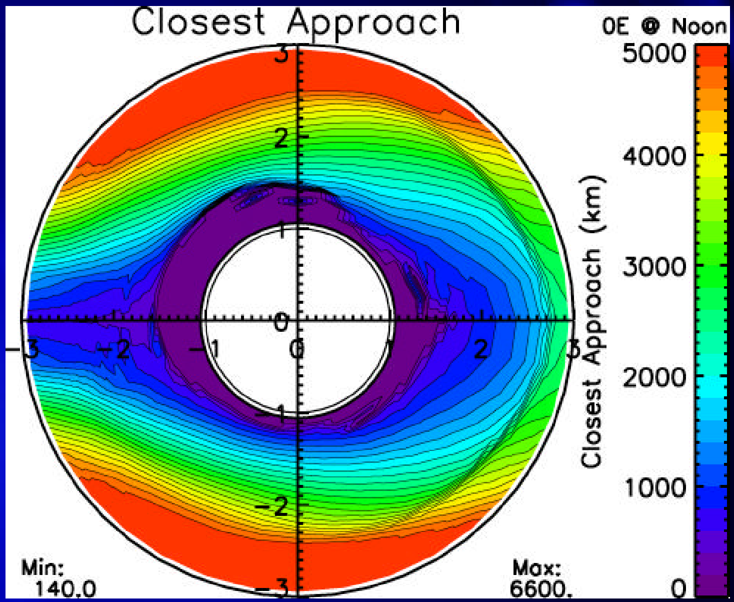
- One crossing (purple): draped (high-alt) or open? (low-alt)
- Two crossings (green): open? (med-alt on dawn side)
- Three crossings (red): draped and S-shaped (high-alt near -Y axis)
- Are "open" lines really open?
  - We cannot tell because of resolution issues screwing up the tracing.

Subsolar Longitude Comparison

Strong Toward

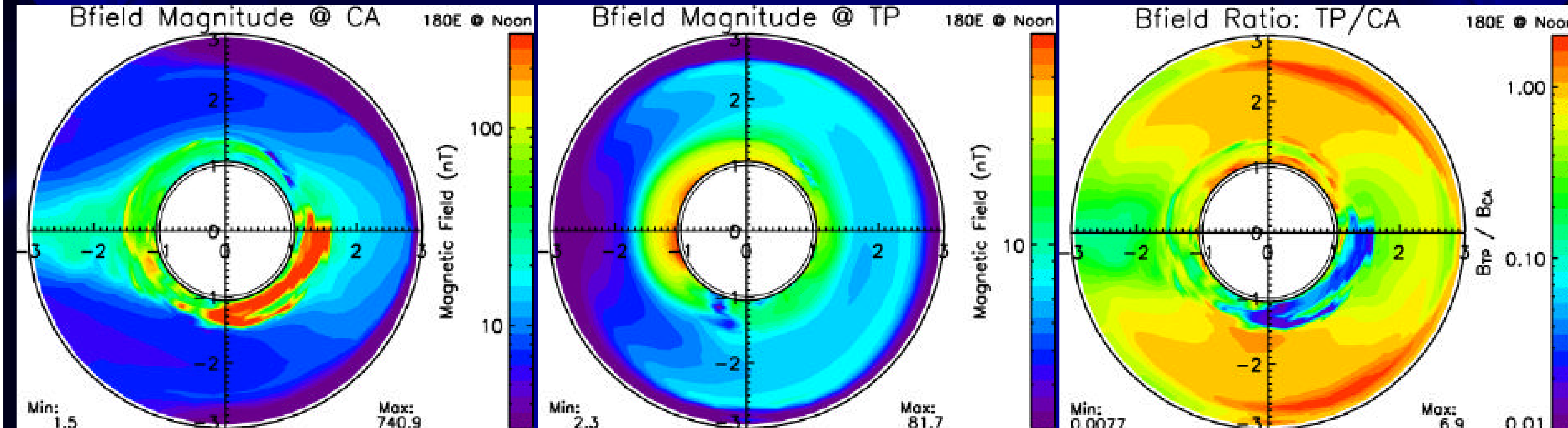


Strong Away



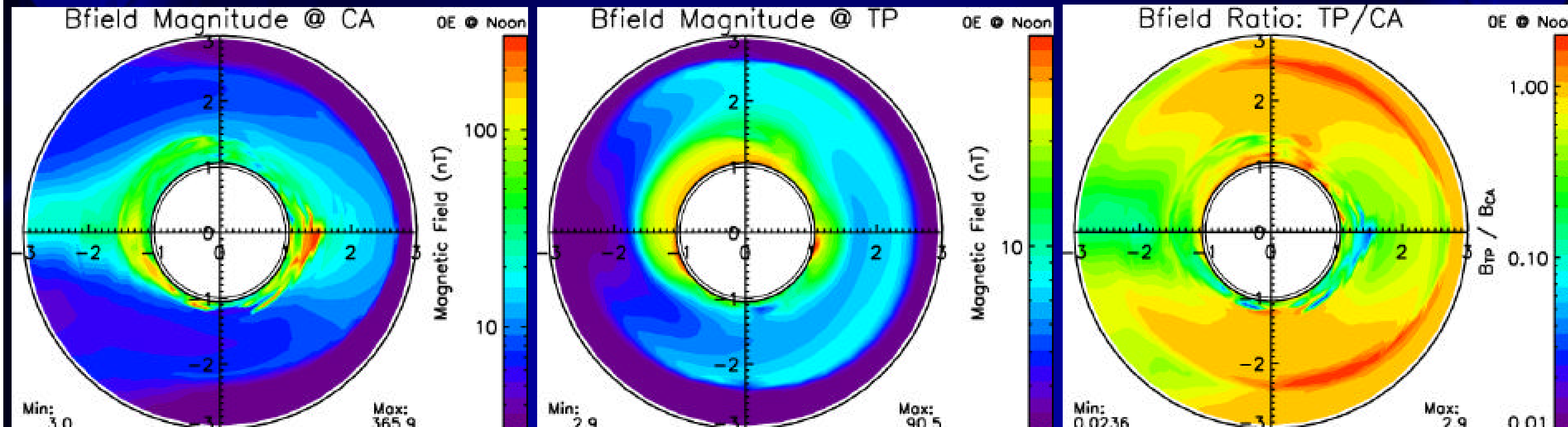
- No significant different around northern hemisphere
  - No big difference near the equator, at dawn or dusk
- Big differences near south pole
  - ~1400 km of small CA versus ~500 km small CA along -Z axis
- Therefore: most of the "140 km CA" region is draped, not open!
- Even so: the 140 km CA region defines ionospheric connectivity

B-field Magnitude and Ratio



- B-field ratio is related to photoelectron pitch angle extent
- LNICs: most have values near unity
- Open LICs: most have values near 0.01
- Draped LICs: widely varying from 0.01 to 1
  – Northern hemisphere: mostly near unity
  – Southern hemisphere: dawn > 0.1, dusk < 0.1

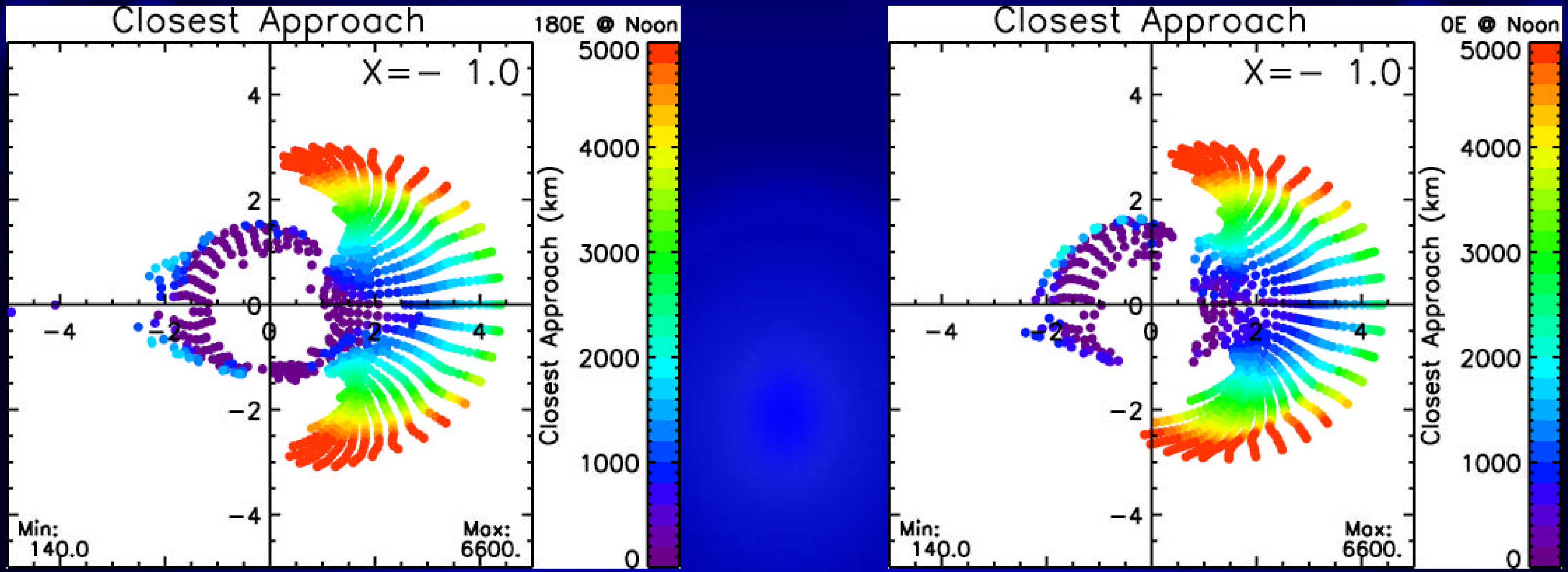
B-field ratios: Strong Fields Away



- Overall: Very similar pattern as with 180E @ noon
  - Biggest difference is that open LICs near south pole are gone
  - Another difference: southern duskside ratios are higher
    - Bigger difference in B(CA) than B(TP) with 180E @ noon values
    - Hmm: evidence of open lines among draped ones for 180E @ noon?
    - Or is it just a difference in pileup topology and strength?

Connectivity at X=-1 R_M

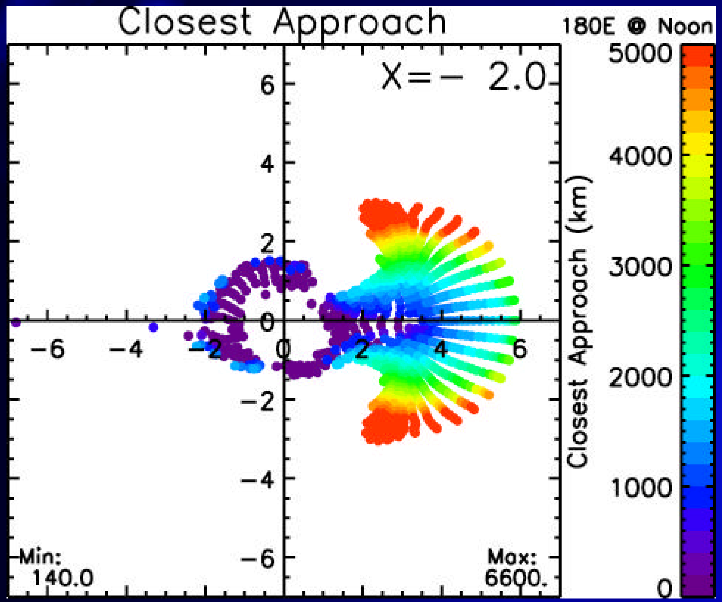
Strong Toward Strong Away



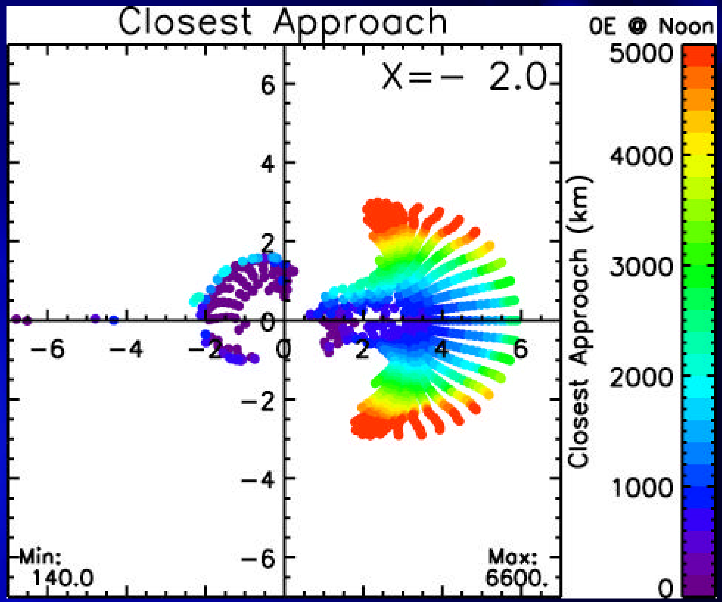
- Each dot: X=-1 crossing of one of the 1188 field lines
  - Collection of all dots shows connectivity to the X=0 plane within 3 R_M
- LICs at X=-1: yes!
  - Circle just beyond 1 RM radius
  - Concentration in northern +Z quadrant
  - Another concentration along +Y axis (out to Y=2 R_M) (this is ~20 LT)

Connectivity at X=-2 R_M

Strong Toward



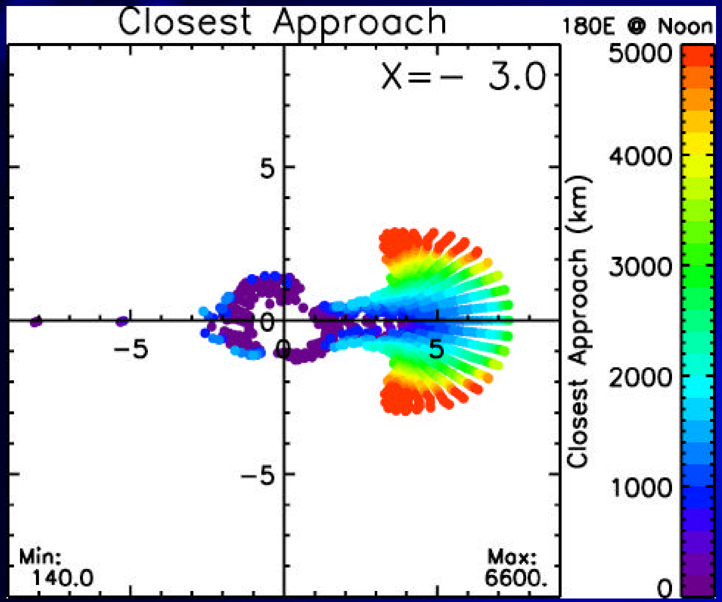
Strong Away



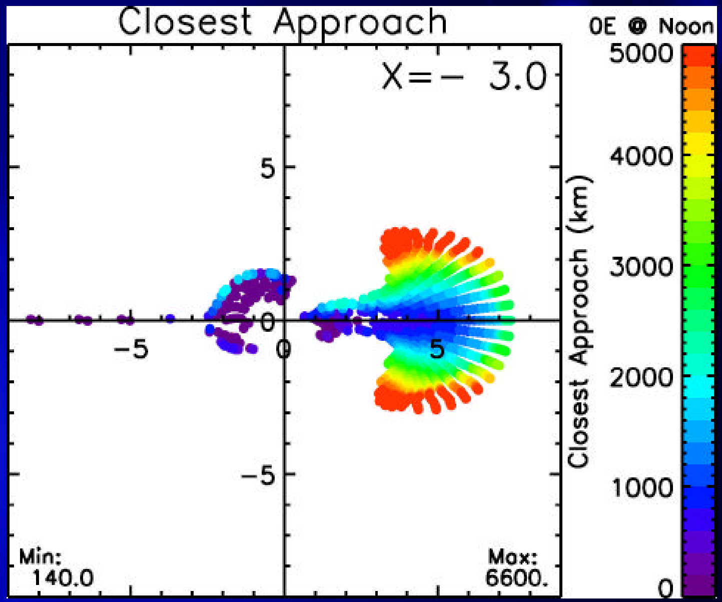
- Similar patterns to the X=-1 plots
- LICs concentrated at 1 RM radius in the plane
- Extension of LICs along +Y axis to Y=3.5 R_M (20:20 LT)
- LNICs: about the same ±Z extent as at X=-1
  - Taking on IMF configuration

Connectivity at X=-3 R_M

Strong Toward



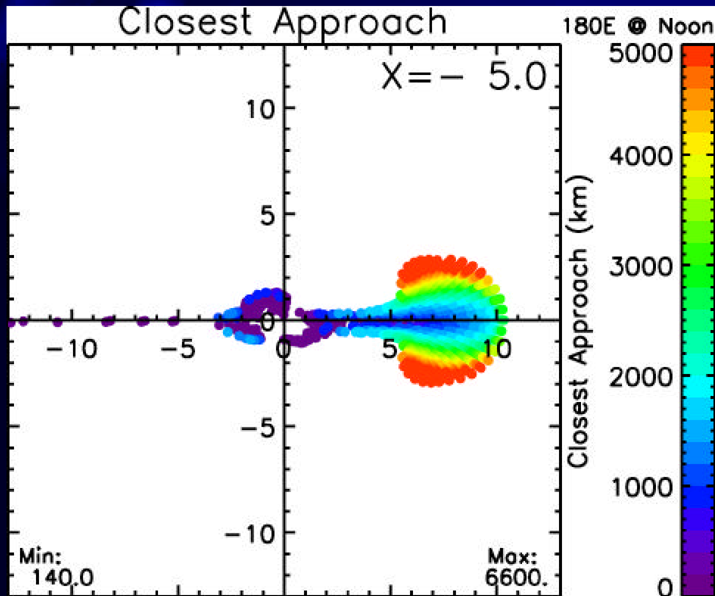
Strong Away



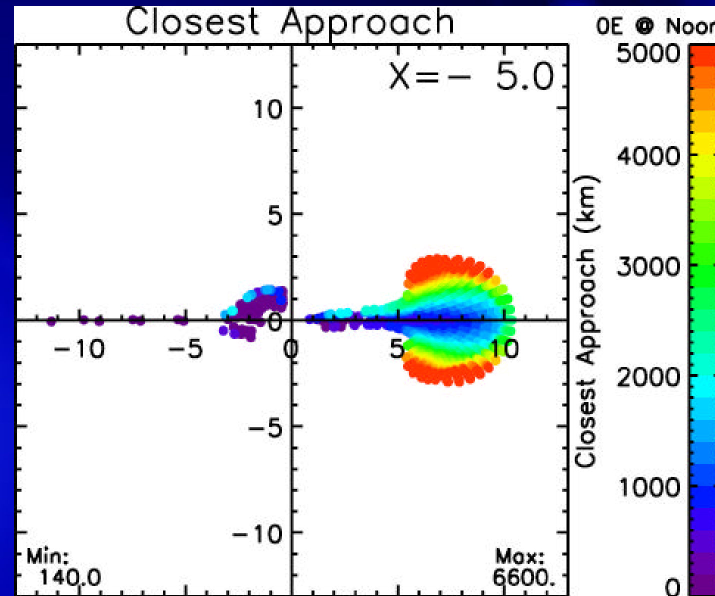
- Again, similar to the previous X=a plane cuts
- What are the points out along the -Y axis?
  - These are some of the S-shaped field lines
  - My routine picks the crossing closest to the TP "degree" value

Connectivity at X=-5 R_M

Strong Toward

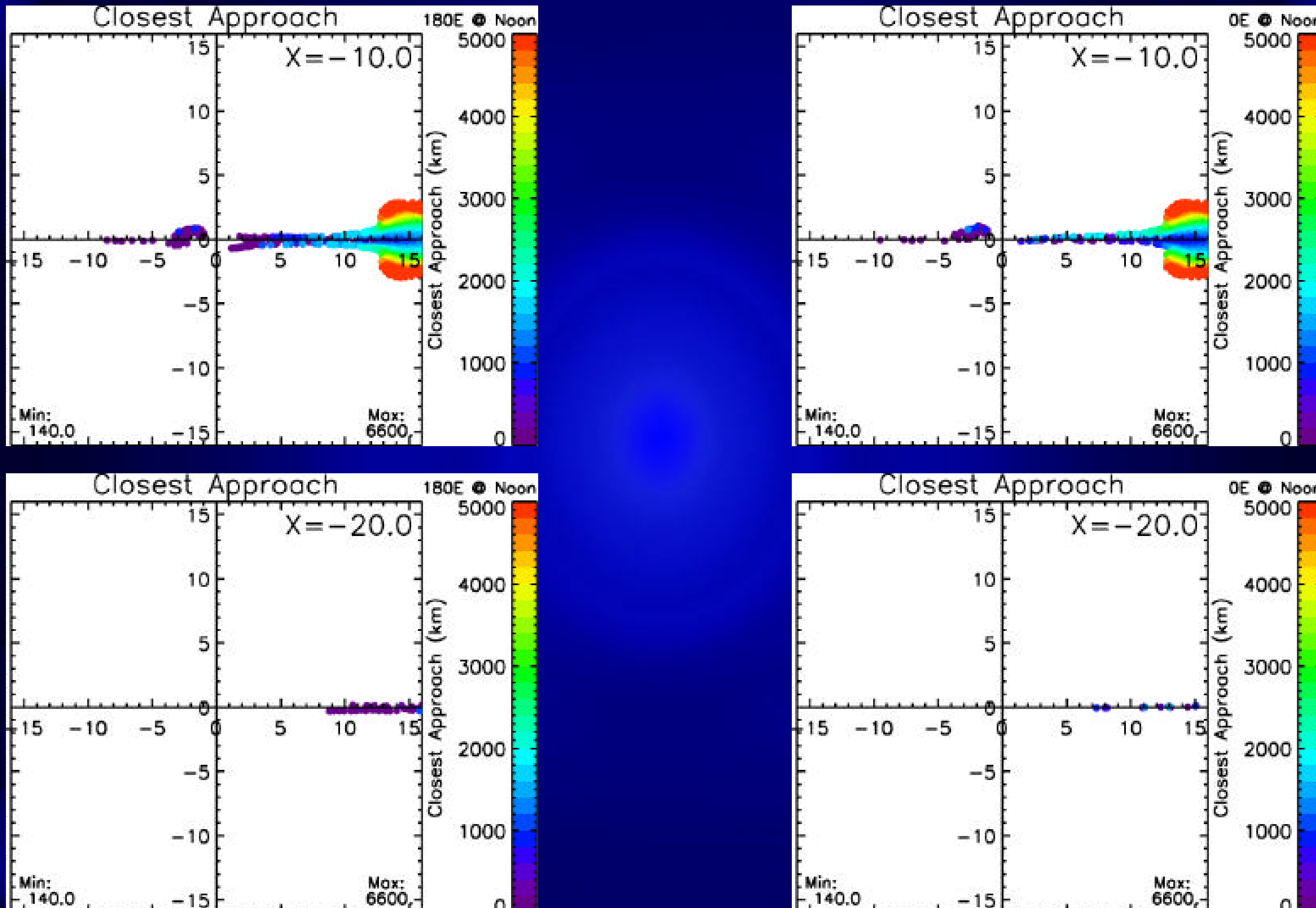


Strong Away



- Again, similar to previous X=a plane crossings
- LICs exist mostly along Y axis
  - Still LICs in the northern -Y quadrant from 1 to 2 R_M radius
  - LICs in southern +Y quadrant in the 180E @ noon case

Connectivity at X=-10 and -20 R_M



LICs still exist at these huge distances downtail!

Other IMF/SW Configurations

- All results for a nominal upstream condition:
  - B_{IMF} = [-2.0,2.2,0], n_{sw} = 3 cm^{-3}, $V_{SW} = V_x$ = -400 km/s
- Changing V_{SW} or IMF will change the connectivity to the ionosphere
  - B_x, B_y changes: compress/expand in ±Y direction
    - Depends on angle wrt V_{SW}: expands with larger angle
  - B_x OR B_y sign change: flip pattern about Z axis
  - B_z nonzero: rotate pattern in Y-Z plane
  - V_y nonzero: shift pattern in ±Y direction (varies with X)
    - Shift is bigger at more negative X values
  - V_z nonzero: shift pattern in ±Z direction (varies with X)
  - P_{dyn} increase: increase number of LICs
    - Magnetic pileup peak must be bigger

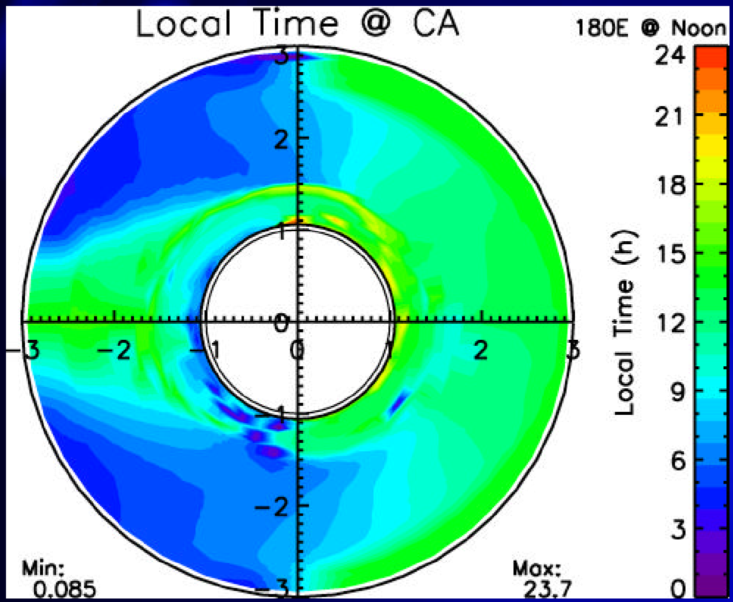
Conclusions

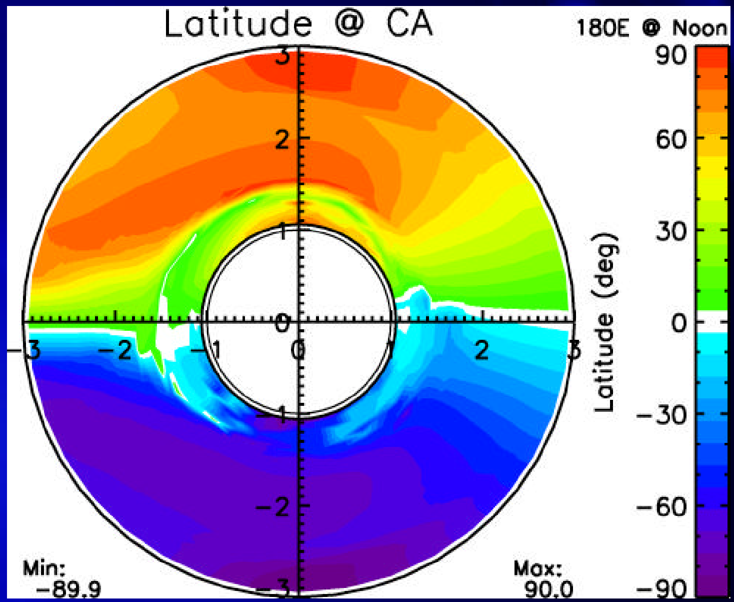
- ASPERA-3 Observations
  - Atmospheric photoelectrons seen at high altitudes across a broad latitude range
    - Usually centered around the equatorial plane, but not always
  - Only a few sectors in width, indicating a limited pitch angle extent
  - Sporadic or continuous, can last minutes or hours
- Case Study Results
  - Large |B| decrease along field lines results in a narrow pitch angle extent for the photoelectrons above 1000 km
  - Magnetic field is connected to ionosphere and the electron distribution is similar
  - Observed and modeled PA extents and offsets are similar
- Field Line Analysis
  - At X=0, altitudes up to 1000 km are ~always connected to the ionosphere
  - At X=0, altitudes up to 2500 km are connected in the [-y,+z] quadrant
    - Also in the [+y,-z] quadrant with 180° subsolar longitude
  - At X=-a, connectivity reduces to a thin plane near Z=0
    - Extended along the +y axis (IMF effect)
    - Near ~1 R_M from the x-axis in the [-y,+z] quadrant
  - Changing the SW or IMF will rotate/distort/shift the connectivity

The End

Extra slides follow...

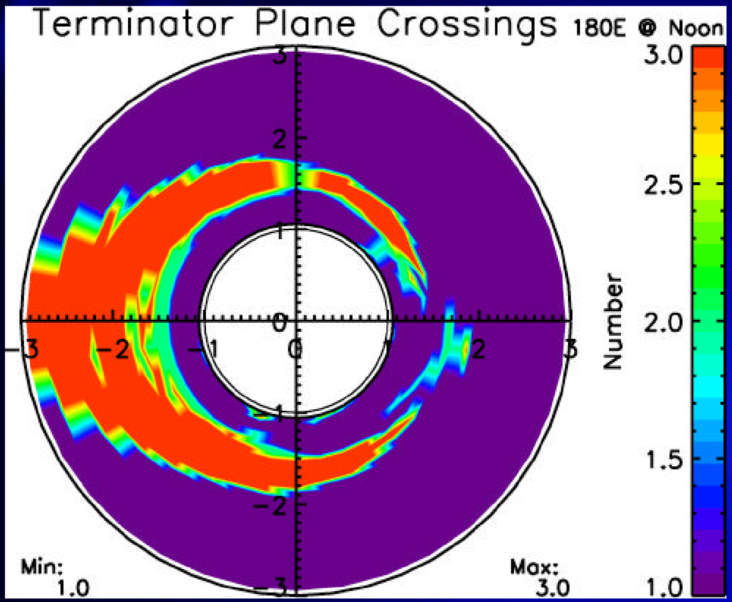
Location of Closest Approach

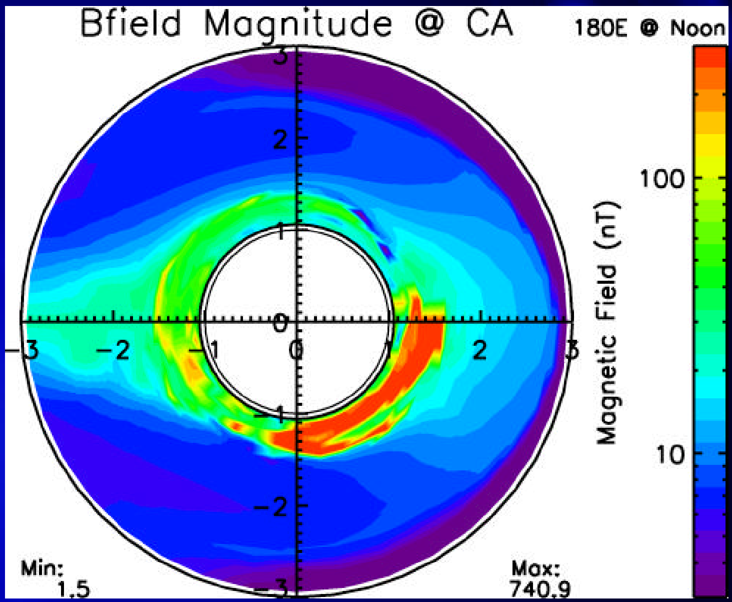




- Definition: "LIC"= lines with ionospheric connectivity
- Definition: "LNIC"=lines with no ionospheric connectivity
- LT of 14 is common for both LICs and LNICs
- Some LICs connected on the nightside (purple and yellow)
- LIC latitude of CA: an indicator of open or draped field lines?

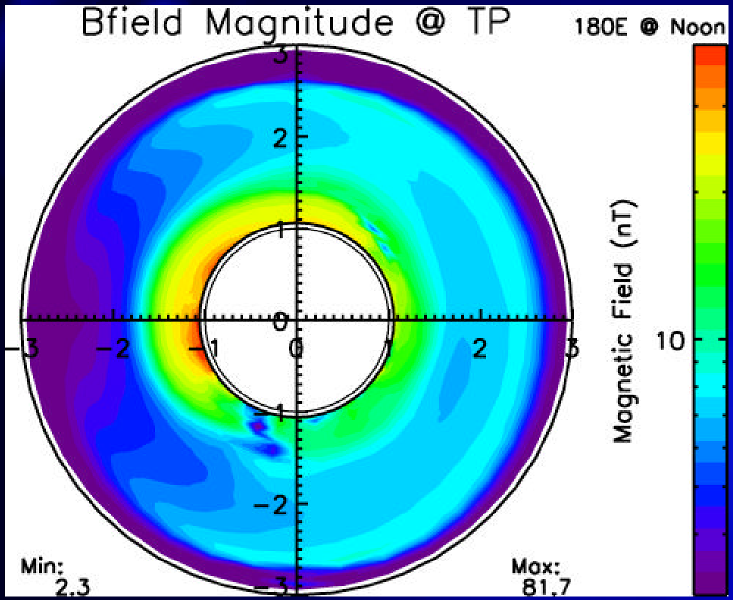
Field Magnitude @ Closest Approach

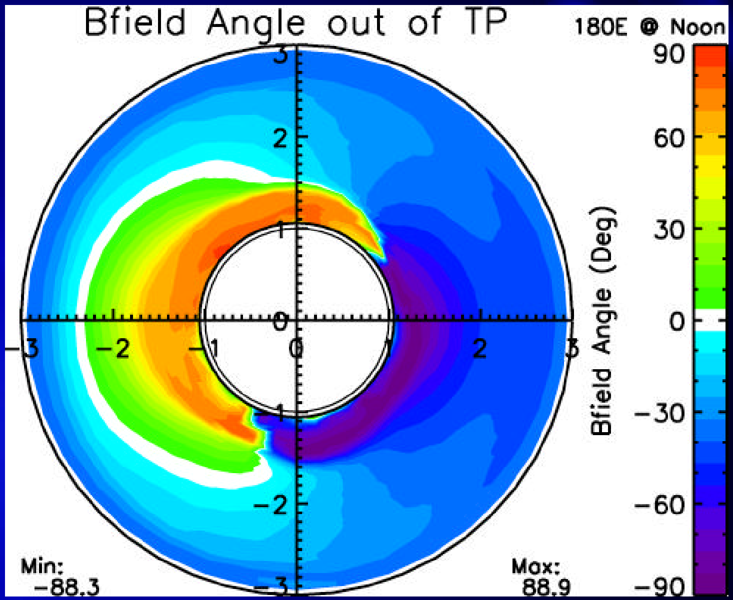




- Good indicator of bow shock!
- For triple-crossing lines: B(CA) can help show continuity
- Open lines near south pole: 100s of nT at CA (140 km)
- Draped LICs: up to 300 nT for those with CA near pileup peak
- Draped LNICs: up to 20 nT, usually below 10 nT

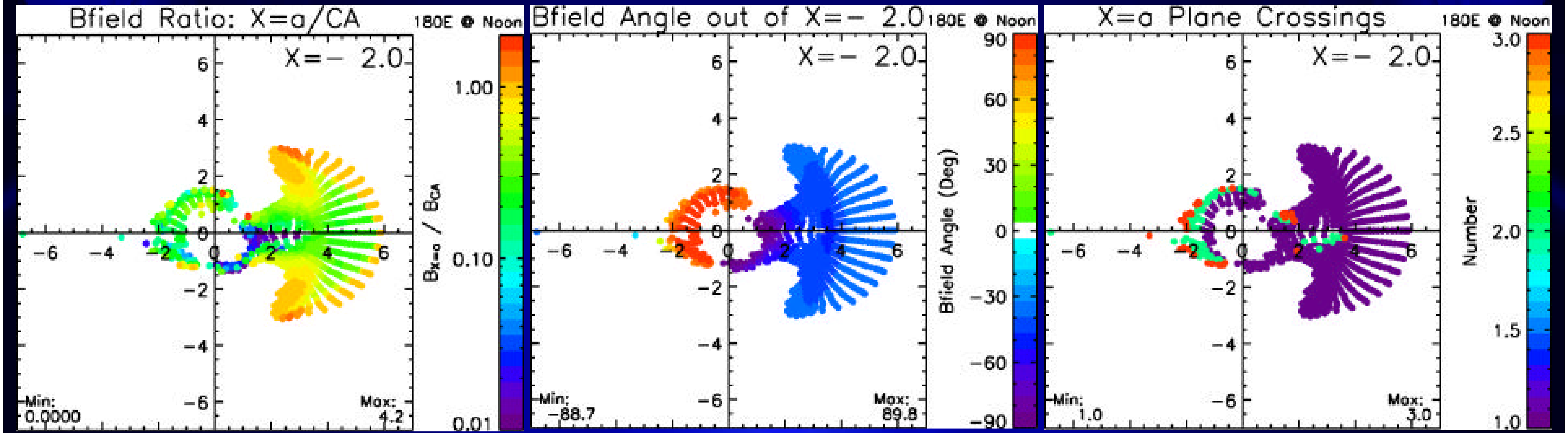
B-field in Terminator Plane





- Magnitude is usually < 10 nT, except close to Mars
- Angle is usually a bit negative, like applied IMF
- Positive region on dawnside: S-shaped draped IMF lines
- White region on dawnside: inflection of the S-shaped lines
- Purple region across southern duskside: nearly anti-sunward LICs

B-Field at X=-2 R_M



- Field Ratio: indicator of LIC of LNIC field lines on duskside
  - LNICs: green or yellow
  - LICs: blue or purple, but ratio is not going much below 0.01
  - On dawnside, all are LICs
- Angle: red and purple lines are nearly parallel with X axis
- Angle: blue lines are taking on IMF angle
- X=-2 plane crossings: dawnside still shows a lot of S-shaped lines