The Smallest Magnetosphere as a Model for the Largest

Margaret G. Kivelson\textsuperscript{1,2}
Xianzhe Jia\textsuperscript{2}

1. Dept. of Earth and Space Sciences, UCLA
2. Dept. of Atmospheric, Oceanic and Space Sciences, Univ. of Michigan
Why Heliopause/Ganymede at the Russell Symposium?

• Chris is always intrigued by exciting new observations that are not fully understood. (Observations led by a former Russell student.)

• This contribution proposes that new insight arises by examining similar processes in different space systems – an approach brilliantly used by Chris in numerous contexts.

• So thanks to Chris for showing the way in so many aspects of space physics and for being a very special colleague over many years.

• Happy Birthday!
Many thanks to David McComas and the IBEX team

- The coauthors of this paper are deeply grateful to the IBEX team for making their data comprehensible and widely available.
- Here we put forward some ideas consistent with interpretations that the team has previously published, including an argument for the orientation of B in the Local Interstellar Medium (LISM) and for the sub-Alfvénic conditions upstream of the heliosphere.
- The analysis is based on simulations of Earth and Ganymede.
Symmetry

• Broken symmetry tells a story.
  – “Perhaps the most remarkable aspect of the IBEX Ribbon is that it appears to be ordered by the most likely direction of the draped interstellar magnetic field” [McComas et al., Ap. J. Supp., 2012]. We agree.

• Magnetospheric symmetry can be broken by
  – the orientation of the central magnetic field
    • For the heliosphere, the solar rotation axis;
  – Key directions of the external plasma.
    • The flow vector and magnetic field directions.

• If one or the other of the external parameters is dominant, the symmetry should be manifest.
Locus and symmetry of the ENA ribbon constrains the nature of the interaction

- The location and extent of the ribbon must provide clues to internal or external features.
  - Ribbon is centered **away from** the “nose” of the heliopause identified by direction of interstellar flow.
  - The ribbon is tilted relative to the heliospheric equator, so its location is not dominantly internally controlled.
  - Displaced from galactic plane.
- What’s left? **External** $B$.
- The form of the ribbon suggests that $B_{\text{LISM}}$ dominates the dynamics of the interaction.

If $B$ symmetry dominates flow symmetry, then in LISM:

$$[(\rho v^2)/(B^2/\mu_o)]^{1/2}=M_A=v/v_A \leq 1$$

$M_A<1 \Rightarrow M_F<1$ - no shock.

Aspects of heliospheric interaction may parallel features of Ganymede’s magnetosphere.
Assuming $B_{\text{LISM}}$ dominates dynamics, we propose that the ribbon reveals where plasma is heated by magnetic reconnection. $B_{\text{LISM}}$ must tilt into the flow if northward or along the flow if southward.

This orientation implies if $B_{\text{LISM}}$ is roughly tangent to a spherical upstream surface near the most intense part of the ribbon.

Inside looking out  Outside looking in
Assuming that $B_{\text{LISM}}$ dominates symmetry:

- We conclude that the magnetic pressure $\geq$ dynamic pressure, i.e., the flow of the LISM is sub-Alfvénic ($M_A \leq 1$).
- We suggest that the source of “energetic ENAs” is reconnection at the heliopause.
- Further insight arises from considering properties of the only known magnetosphere within a sub-Alfvénic plasma, Ganymede’s magnetosphere that forms within Jupiter’s magnetospheric plasma.
  - Using simulations, we compare Ganymede with Earth to investigate upstream conditions that bracket the range that we propose for the LISM.
- Start with a simulation* of Earth’s magnetosphere with $B$ tilted as proposed for the LISM.

* the Michigan BATSRUS global MHD model
Reconnection increases $T$ on parts of the magnetopause.

High $T$ is almost symmetric about “nose”

Earth: $M_A=8$, $M_F=6$

High $T$ center shifts south of “nose”

Earth: $M_A=2.3$, $M_F=2.2$

As $M_A$ decreases, heating shifts closer to regions where $B_{ext}$ is tangent to the upstream surface.

Next → Ganymede. Its magnetosphere has been simulated with high fidelity (compared with Galileo data).

- The internal field and plasma conditions differ greatly from conditions in the heliosphere.
- Nonetheless, hints of the nature of the sub-Alfvénic interaction can be extracted from existing Ganymede simulations.
- The Ganymede simulation shows upstream reconnection is intermittent but recurrent, close to regions where the external field is tangent to the magnetopause.
- Reconnection heats the plasma.

Next, an example from a run of the Ganymede simulation for external conditions that match the LISM configuration proposed by McComas et al. [2012].
Compare Earth with Ganymede
Asymmetry of heating increases as $M_A$ decreases.

Earth ($M_A = 8$, $M_{ms} = 6$)

Ganymede $M_A = 0.4$; $M_{ms} = 0.3$

(Focus on upstream regions as downstream dominated by symmetry of internal B.)
Finally: sample temperature on “plane of sky” to collect “ENAs” from Ganymede’s higher T regions and compare (view from inside out).

- Downstream dynamics depend on internal field structure, so ignore the downstream regions (partly masked).
- The upstream “hot spot” distribution at Ganymede corresponds quite closely to the observed ENA ribbon.
And once again: views from upstream

- The field polarity near heliopause off heliospheric equator is steadily positive [Burlaga and Ness, 2011]. If reconnection plays a role, this unipolar field resolves the ambiguity of the orientation of $B_{\text{LISM}}$. It is oriented southward with a component along the flow.
Reconnection can account for energy dependence of ribbon.

- Ribbon center (dashed lines added to McComas et al. [2012] figure, assumed at locus of tangent $B_{\text{LISM}}$) does not change with energy.
- Reconnection heats ions by roughly $4E_o/M_A$ above background ($E_o$), implying that locally more ENAs will be produced in the keV range.
- Charge exchange cross sections in keV range decrease with energy, so locally energized ions can move farther N-S from source region before converting to ENAs, accounting for broadening of ribbon at higher energies.
Can charge exchange send ions accelerated along B in direction towards the earth?

• Not hard: e.g., ion kinetic effects scatter particles in pitch angle rather quickly: Lottermoser et al. [1998]** simulated reconnection in a thin current sheet, reporting: “The thin current sheet is unstable. At about 200 ion inertial lengths away from the neutral line the instability has reached a nonlinear state and the cross-tail current becomes patchy; the incoming and ejected cold lobe ions are isotropized in the ensuing magnetic field and thus constitute a hot plasma sheet distribution.”

• Using estimates of $v_A$ of LISM, we find that at 166 ion inertial lengths, 1 keV ions have propagated no more than 0.1 AU along the field.

Summary and expectations

- The symmetry of the ENA belt on the heliopause is consistent with distribution of “hot spots” in a Ganymede ($M_A<1$) simulation.
- Ganymede simulations may help us understand distribution of sources and their energy dependence.
- LISM flow is probably sub-Alfvénic and we can infer the field orientation.
- Noting how the global configuration of Ganymede’s magnetosphere differs from that of a planetary magnetosphere, we anticipate that the upstream heliopause is far blunter than in most simulations or cartoon representations.