Inferring the Interstellar Magnetic Field Direction from Energetic Neutral Atom Observations of the Heliotail

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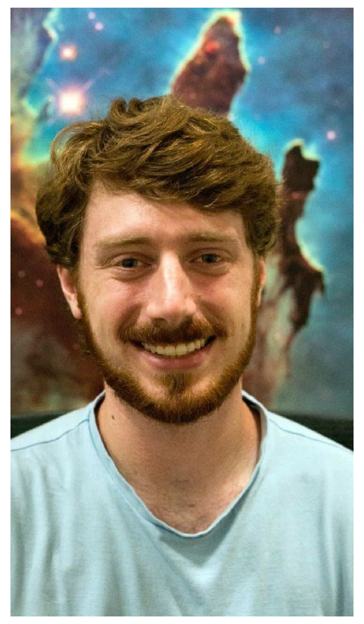

Overview

- Energetic Neutral Atoms (ENAs) can be used to indirectly study the structure of the heliosphere
- ENA imagers such as IBEX-Hi (0.52-6 keV) provide important observations of the heliosphere, but ENA models required to decipher
- ENA observations of the heliosphere have shown an evolution with solar cycle (McComas et al. 2020)
- Zirnstein et al. (2016a) identified a 5-lobe structure in IBEX-Hi ENA observations of the heliotail
- Dayeh et al. (2022) found a rotation of the heliotail lobes over the solar cycle
- To date, global ENA models have been unable to reproduce the inclination of the high latitude heliotail lobes, even when including solar cycle variations
  - One key difference between the global ENA models is the interstellar magnetic field (B_{ISM}) used
  - Lallement et al. (2005, 2010) constrained B_{ISM} to lie in the hydrogen deflection plane (HDP) with respect to the pristine interstellar flow (herein, α_{BV} is the angle between the B_{ISM} and interstellar flow directions in the HDP)
  - Zirnstein et al. (2016b) inferred the direction and magnitude of the B_{ISM} by fitting the IBEX Ribbon center assuming a secondary ENA mechanism as the source ($\alpha_{BV} = 40°$)
  - Izmodenov & Alexashov (2020) inferred the direction and magnitude of B_{ISM} by determining which parameters best matched the Voyager termination shock and heliopause crossings in their kinetic-MHD solution ($\alpha_{BV} = 20°$)
- Here we attempt to isolate the effect of the B_{ISM} on the inclination of the heliotail lobes to infer the interstellar magnetic field characteristics

Method

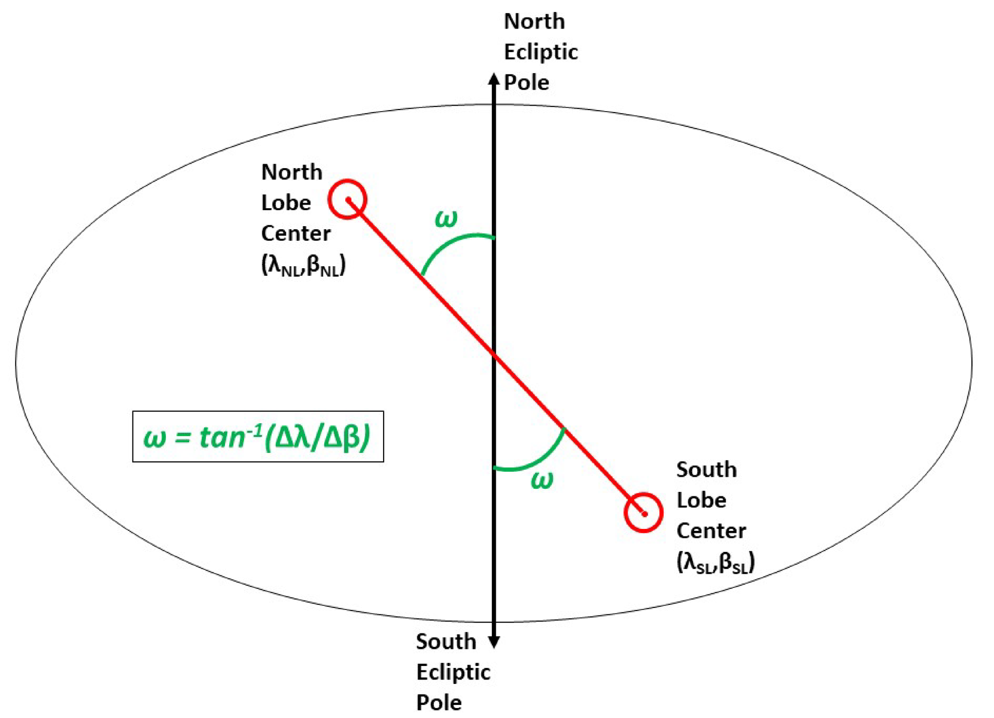

Figure 1. Cartoon depicting tail-centered Mollweide projection showing the inclination angle (ω) of the high latitude heliotail lobes, with ω defined by the angle of the north/south lobes relative to the solar meridian.

- We simulate the heliosphere using a kinetic-MHD solution (Michael et al. 2022) with different solar and interstellar conditions
- Using the ENA model from Kornbleuth et al. (2023), we produce synthetic ENA maps from each solution to compare with IBEX ENA observations
- We compare the inclination of the heliotail lobe to determine the effect of different conditions on the evolution of the heliotail, and by extension to investigate the B_{ISM} direction

Cases

Case	α_{BV}	B_{sw} [μG]	SW Profile	λ_{NL}	λ_{SL}	ω
1	40°	29.4	2008	102.0 ± 3.0°	78.0 ± 3.0°	14.0 ± 3.5°
2	40°	44.4	2014	96.0 ± 3.0°	84.0 ± 3.0°	5.0 ± 2.5°
3	40°	29.4	Uniform	102.0 ± 3.0°	78.0 ± 3.0°	14.0 ± 3.5°
4	40°	64.5	Uniform	96.0 ± 3.0°	84.0 ± 3.0°	5.4 ± 2.7°
5	60°	37.5	1995-2017	102.0 ± 3.0°	78.0 ± 3.0°	14.0 ± 3.5°
6	40°	37.5	1995-2017	102.0 ± 3.0°	84.0 ± 3.0°	10.6 ± 3.5°
7	20°	37.5	1995-2017	102.0 ± 3.0°	90.0 ± 3.0°	6.0 ± 3.0°
8	10°	37.5	1995-2017	96.0 ± 3.0°	90.0 ± 3.0°	3.0 ± 3.0°
Data (12-13)				86.6 ± 1.8°	84.9 ± 2.6°	1.2 ± 2.5°
Data (14-15)				89.3 ± 1.3°	88.0 ± 0.7°	1.0 ± 1.9°
Data (16-17)				83.4 ± 0.2°	83.4 ± 0.3°	0.1 ± 0.4°

Table 1. Different cases utilized in this study. Included is the angle between the interstellar magnetic field and interstellar flow direction in the hydrogen deflection plane (α_{BV}), the solar magnetic field intensity (B_{sw}), the solar wind profile, the longitude of the north (λ_{NL}) and south (λ_{SL}) lobe centers, and the inclination angle of the lobes (ω) as described in Figure 1.

- Cases 1-4: use same interstellar conditions but vary solar conditions
  - Cases 1 and 2 reflect yearly-averaged solar wind from IPS observations (Sokol et al. 2015) and solar magnetic field from OMNI for years 2008 (solar minimum) and 2014 (solar maximum), respectively
  - Cases 3 and 4 have same uniform solar wind conditions (i.e. solar maximum-like) with different solar magnetic field intensity
- Cases 5-8: use identical solar-cycle averaged conditions at 1 au, but only change the B_{ISM} direction, while keeping it in the hydrogen deflection plane
  - Keep B_{ISM} magnitude constant for all cases since at lower limit of predicted magnitude range and higher B_{ISM} intensity would only strengthen effect

Both the Solar Wind and Interstellar Magnetic Field Influence the Tail

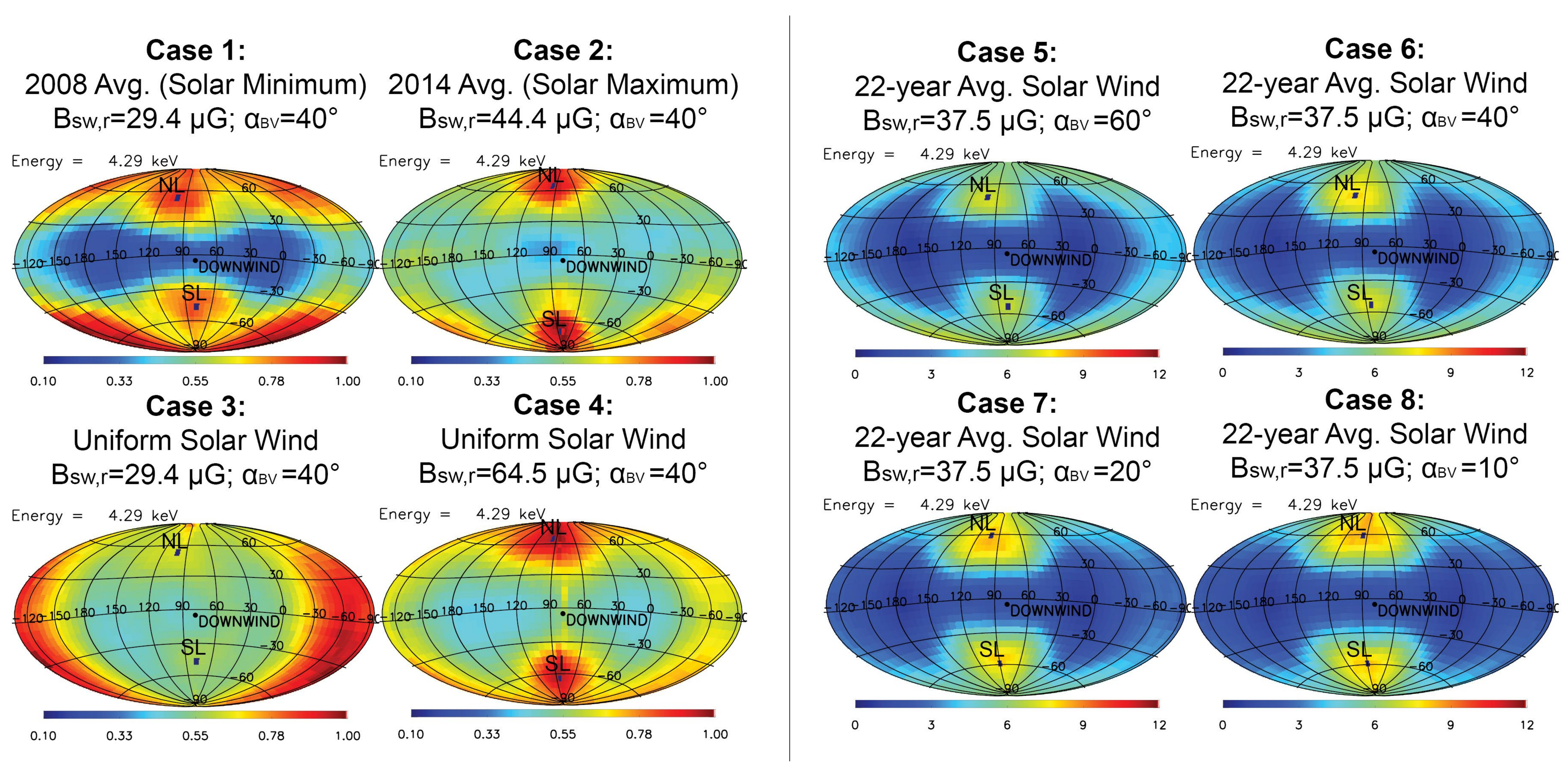

Figure 2. Evolution of the north/south lobe centers with changing solar wind profile and solar magnetic field (maps on left) and with changing B_{ISM} direction (maps on right). Different cases included are listed in Table 1. Cases 1-4 have identical interstellar conditions, while Cases 5-8 have identical solar wind and magnetic field conditions.

The *Solar Magnetic Field* Affects the Rotation and the *Interstellar Magnetic Field* Affects the Inclination

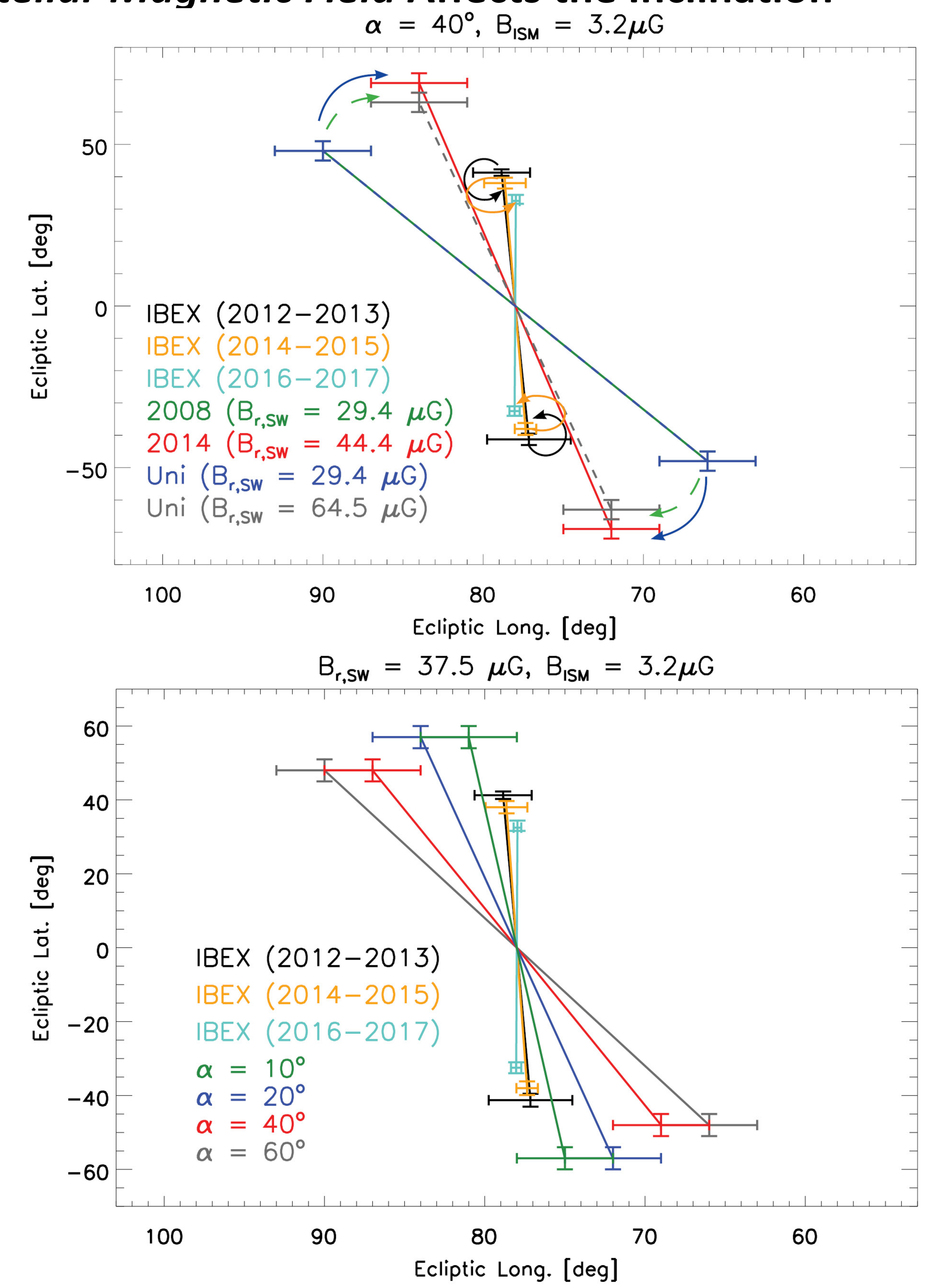

Figure 3. Top: evolution of lobe centers with varying solar wind and solar magnetic field conditions. Bottom: evolution of lobe centers with varying B_{ISM} angle.

- **Lobe centers rotate with varying solar wind conditions, but the centers have larger dependence on solar magnetic field intensity than on solar wind profile**
- Case of solar minimum (i.e. weak solar magnetic field) trends towards maximum inclination of the heliotail
- Different B_{ISM} orientations influence the inclination of the lobes
- **With averaged solar wind/magnetic field conditions, $0° < \alpha_{BV} < 20°$ *gives best agreement with observations***

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