Unresolved questions about th heliosphere

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Motivation

Between many unresolved science questions on the nature of the heliosphere are two fundamental:

- how does the heliosphere look like? and
- where is the „nose” of the heliosphere?

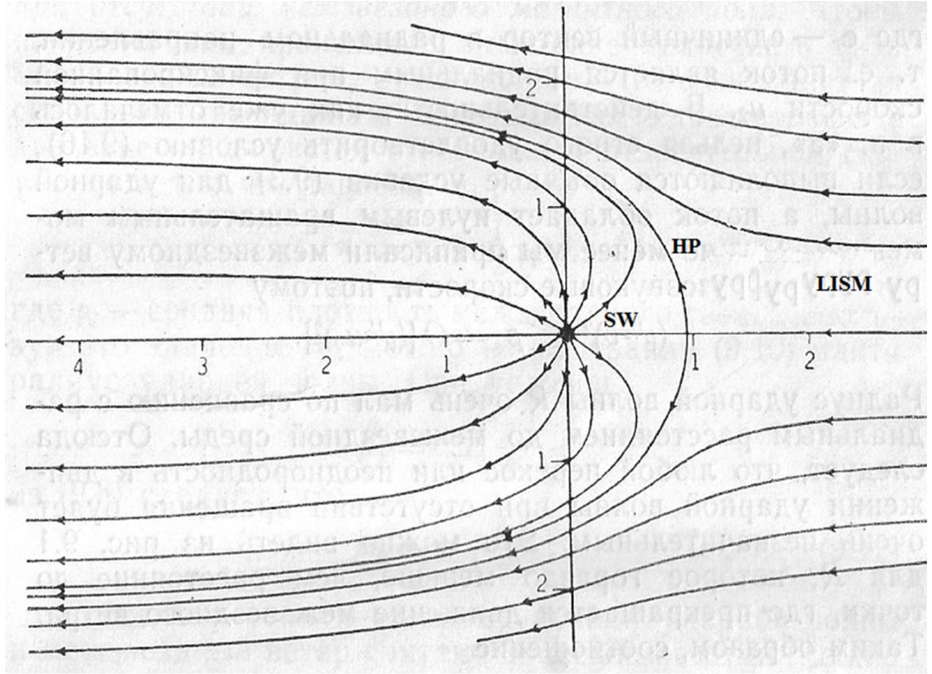
The aim of this presentation is to try to answer these questions.

Introduction

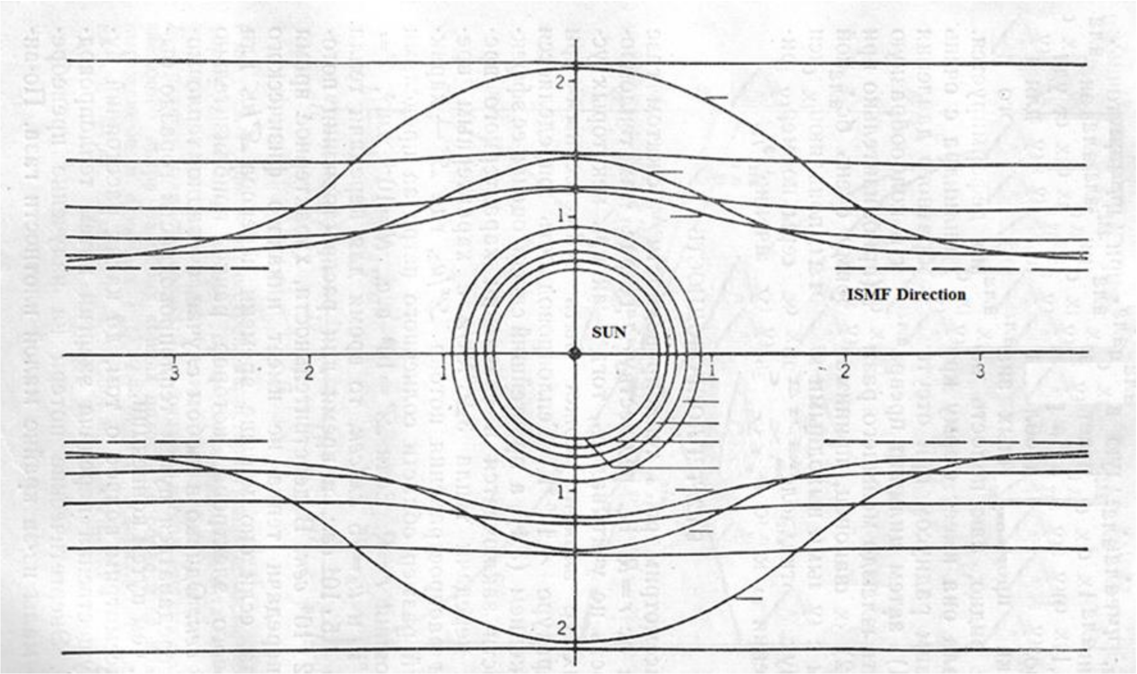
The current state of knowledge about the interaction of the Sun's expanding corona with incoming Local InterStellar Medium (LISM) in which the Sun moves is due to a more than 60-year history of building models of the heliosphere, which is creating from this interaction. In 1958, Parker proved that the solar corona is not static and must expand into space. He called this expansion the solar wind (SW). The first models proposed by Parker, which did not require complex numerical simulations and at the same time, in my opinion, become the basis for understanding the heliosphere were:

E.N. Parker, Interplanetary Dynamic Processes, 1963

Interaction of subsonic solar wind with the interstellar medium

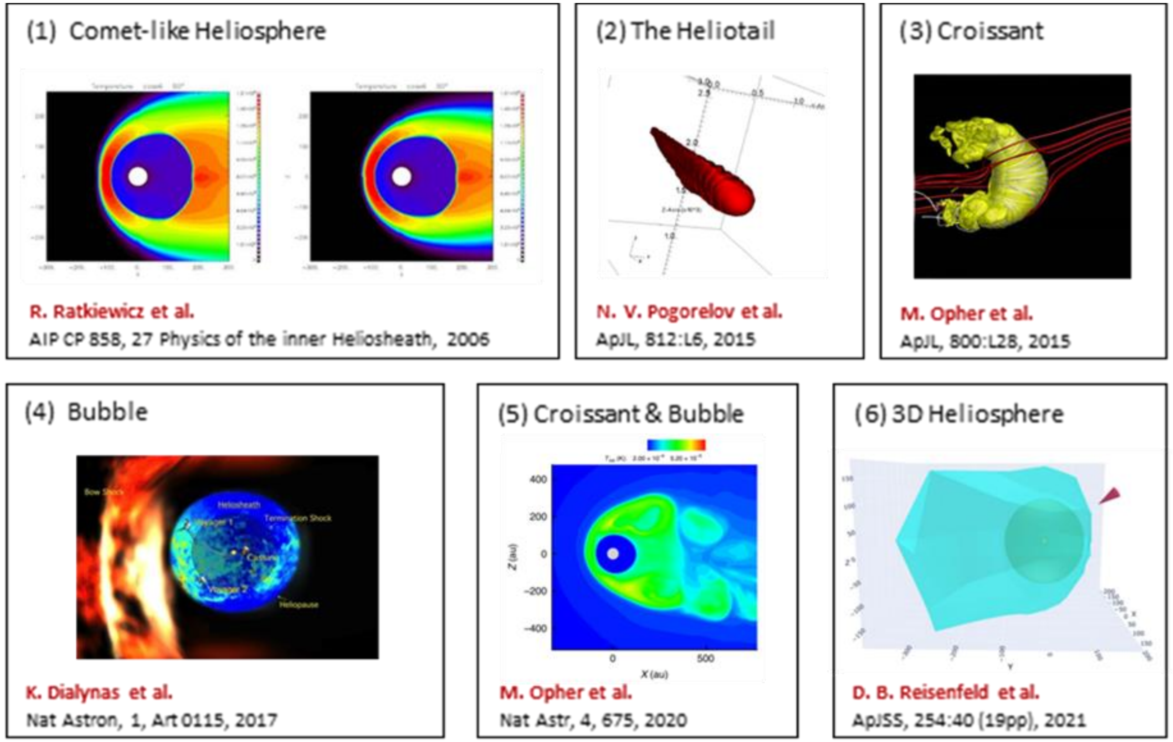


Outflow of the solar wind into the interstellar magnetic field



These models became the basis for all later numerical hydrodynamic and magnetohydrodynamic models of heliosphere.

Old paradigm vs New paradigm



For a long time, the heliosphere was thought to have the shape of a comet with a rounded nose and tail [1-2]. This standard picture of the heliosphere has been widely accepted as the dominant paradigm. However, the latest modeling and observations are challenging this paradigm. In recent years, other shapes of the heliosphere have been proposed, such as the croissant [3] (based on Voyager 1 data), or a bubble [4] (based on Cassini data). A model was also created that combines both these visions, i.e., it contains elements of both a croissant and a bubble [5]. Recently, a 3D map of the heliosphere was created based on the data from the IBEX mission [6].

Conclusion 1

On this basis we cannot decide how does our heliosphere look like.

The answer to the first question is up to now negative

Resolution of the second question?

Going to the second question, we remind that Parker already in 1958 pointed to the very important role of the ISMF in the interaction of both plasmas: SW and LISM.

It was reflected in application the so-called Newtonian Approximation (NA) to study the problem where is the „nose" of the heliosphere.

Newtonian Approximation

Consider two **highly supersonic** plasmas: SW and LISM, with parallel ISMF to the LISM velocity, inflowing onto each other. A separation surface called heliopause (HP) is formed between them, and on both sides of the HP two waves: termination (TS) in the SW and bow shock (BS) in the LISM are formed. The shapes of the HP, TS, and BS at the frontal side in case of highly supersonic plasmas are very similar. The distance from HP to both waves is short. The intersection of HP with the axis parallel to the LISM velocity vector passing through the center of the Sun is defined as the „nose" of the HP.

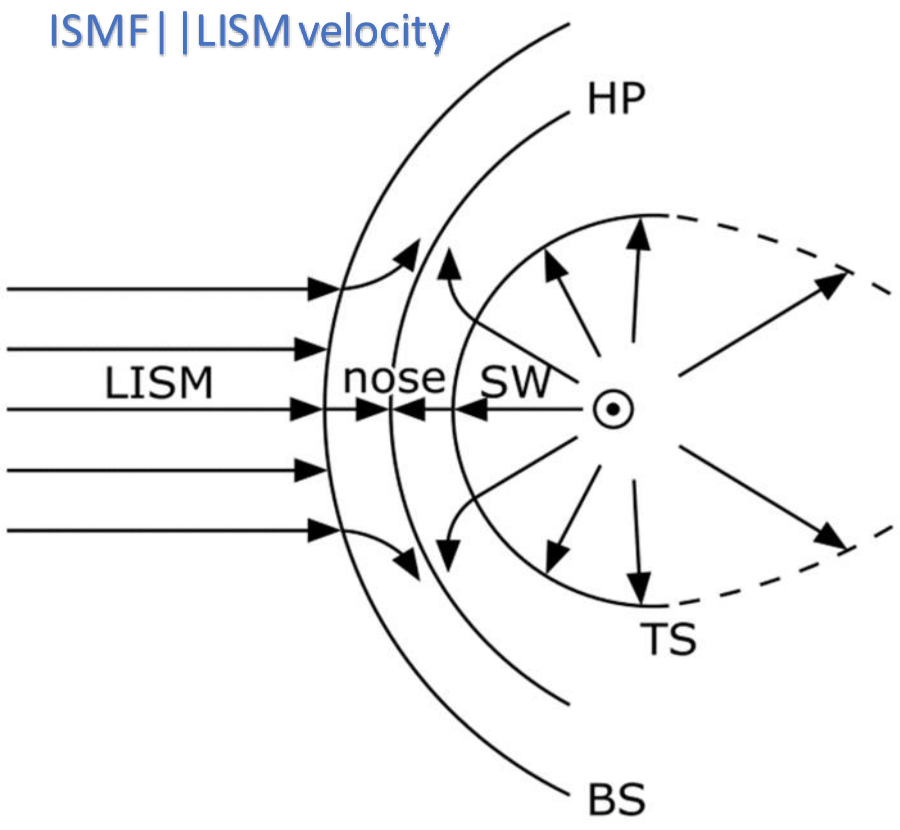


Figure on the basis of Baranov et al., 1981

Knowing the physical parameters of both undisturbed plasmas, we can find the shape of the HP from the equation expressing the equality of the normal components of the total hydromagnetic momentum flux (the sum of the ram, magnetic field and thermal pressures) on both sides of HP. This procedure applied to the heliopause is expressed by an equation:

$$(\Pi_{ik} N_i N_k)_{LISM} = (\Pi_{ik} N_i N_k)_{SW}$$

where

$$\Pi_{ik} = p\delta_{ik} + \varrho v_i v_k - (B_i B_k - B^2 \delta_{ik}/2)/(4\pi)$$

represents the unperturbed total (Reynolds and Maxwell) stress tensors.

Fahr et al., 1986

H.J. Fahr, R. Ratkiewicz & S. Grzedzielski
Adv. Space Res. Vol. 6 No. 1 1986

Results of the NA approach confirm importance of the ISMF in the SW-LISM interaction and reveal deviation of the heliopause „nose" in dependence of the ISMF magnitude and direction.

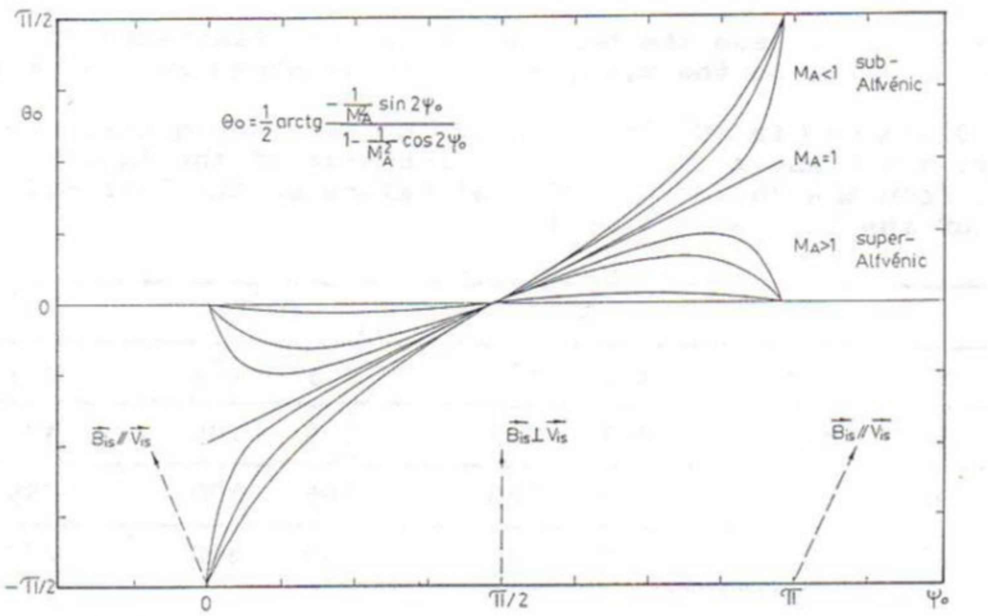


Fig. 2. Dependence of the angular deviations Θ_0 of the HP „nose" for different angles of inclination Ψ_0 of the interstellar magnetic field. The curves are parameterized by Alfven Mach number $M_A = V/V_A$

Figure 2 Fahr et al., 1986

H.J. Fahr, R. Ratkiewicz & S. Grzedzielski
Adv. Space Res. Vol. 6 No. 1 1986

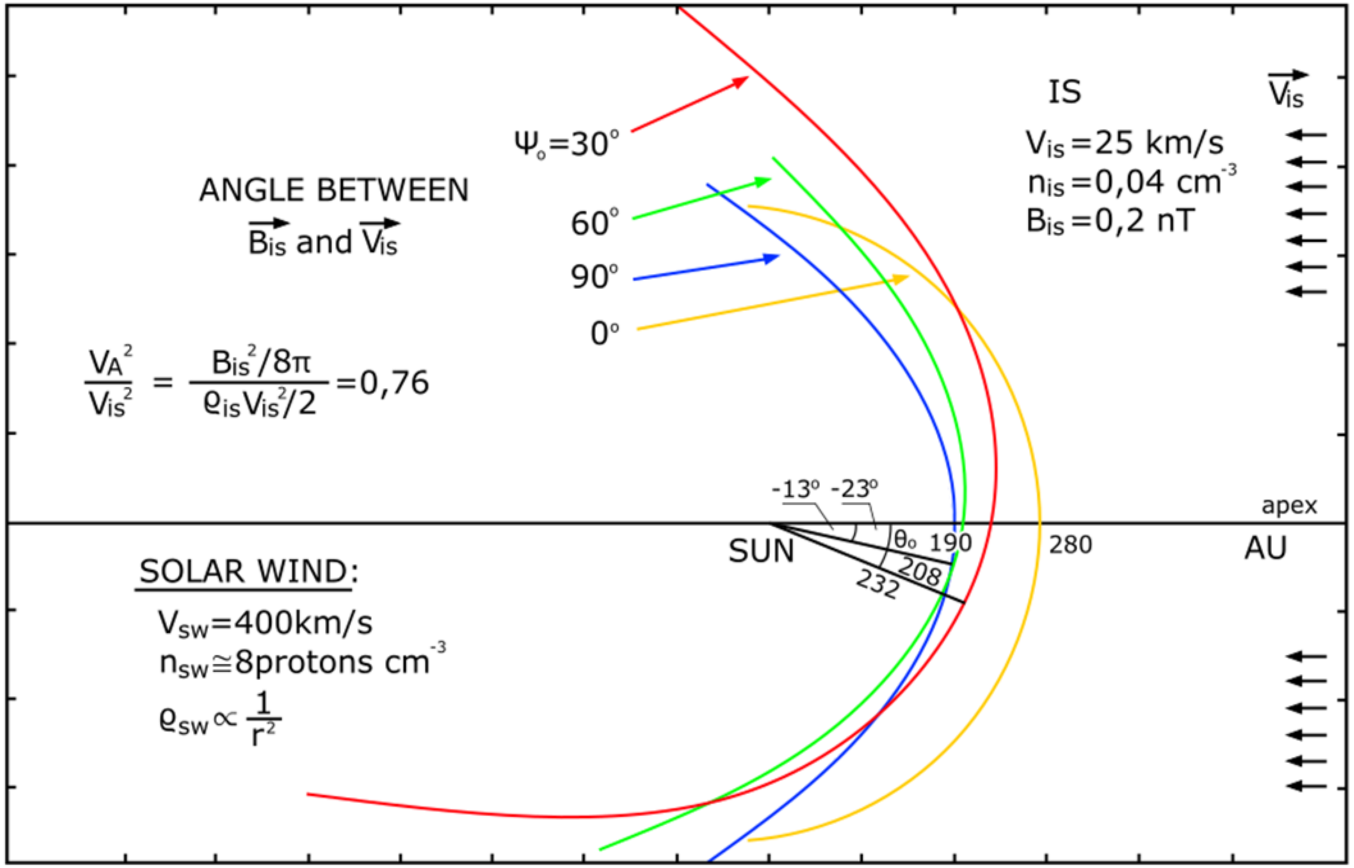


Fig. 3. Shape of the frontal heliopause in the xy-plane for different inclination angles Ψo of the LISM magnetic field

Figure 3 Fahr et al., 1986

This dependence detected by the NA method after almost a decade has been confirmed by 3D magnetohydrodynamic (MHD) numerical simulations of the shape and structure of the heliosphere by Ratkiewicz et al. [3-4]

Ratkiewicz, Barnes, Molvik et al.
Astron. Astrophys. 335,p.363 (1998)

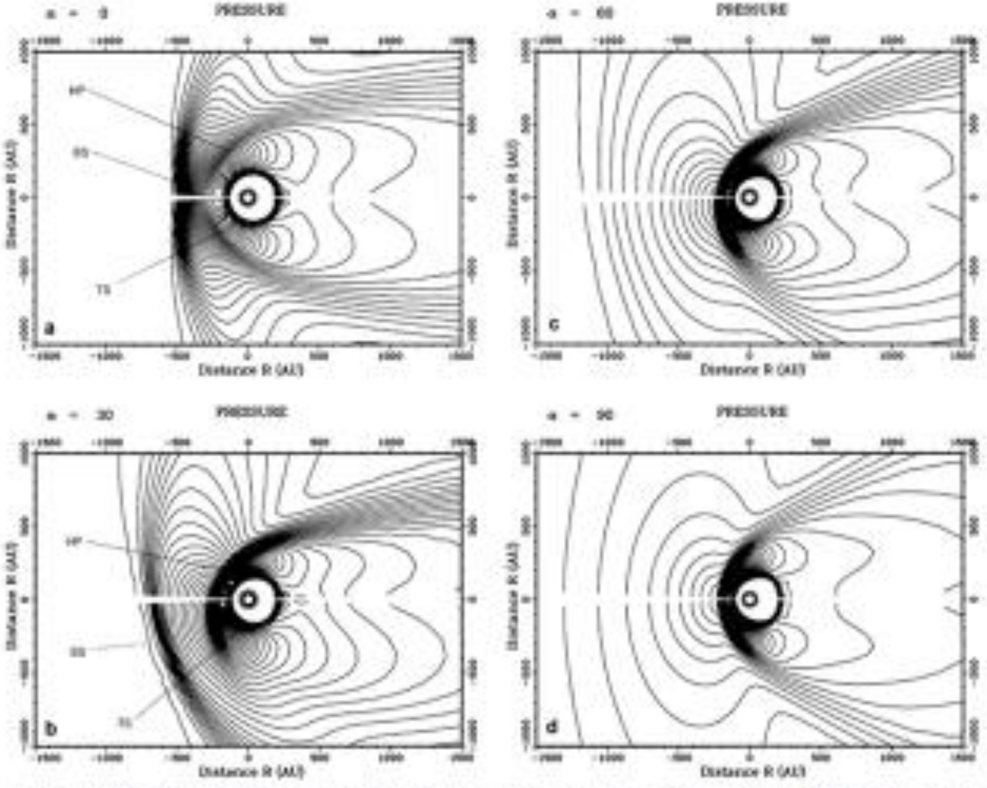
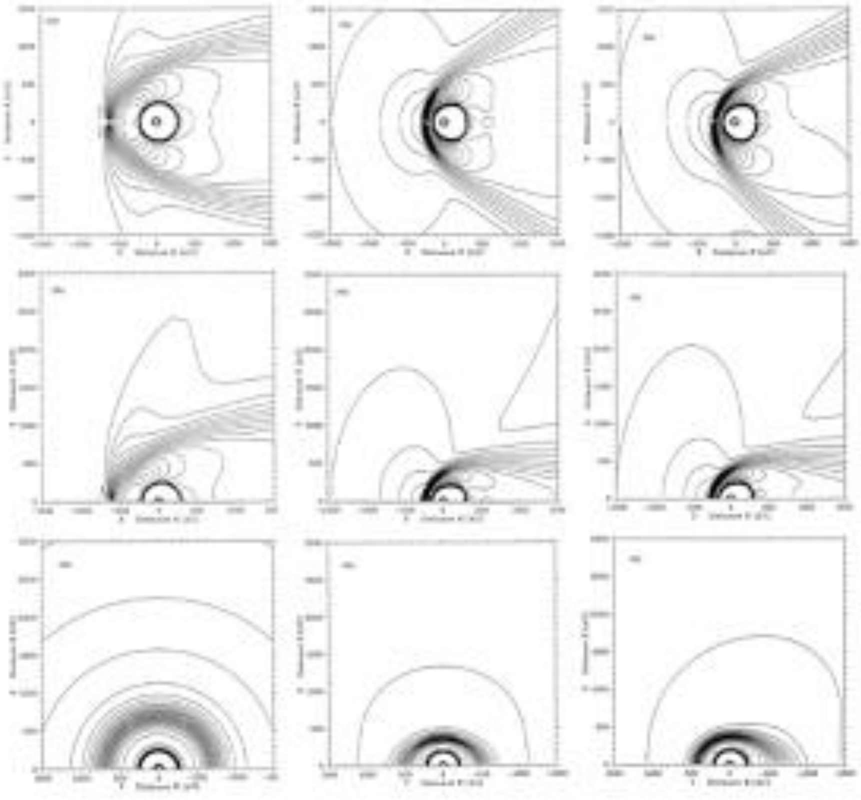


Fig. 6a–d. Shape of the heliospheric boundary region as shown by thermal pressure contour plots for inclination angle α equal to a 0°, b 30°, c 60°, d 90°. VLISM Alfvénic Mach number = 1.5. Positions of termination shock (TS), heliopause (HP) and bow shock (BS) are as indicated in Figs. 6a and 6b

Deviation of the „nose"of heliopause due to interstellar magnetic field for inclination angles $0^\circ < \alpha < 90^\circ$

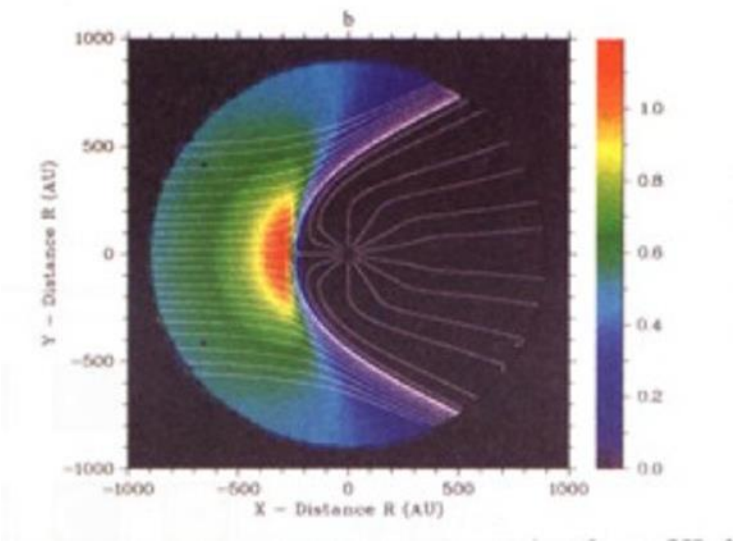
Ratkiewicz, Barnes, Spreiter
JGR, 105, 25,021-25,031 (2000)



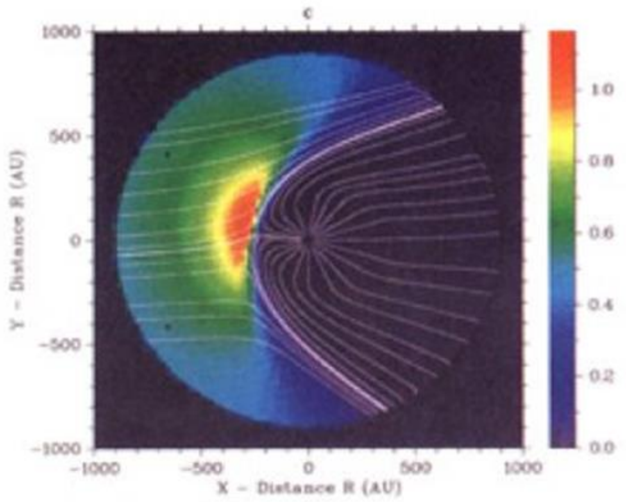
Asymmetries of the heliosphere: deviation, flattening and distortion caused by interstellar magnetic field

These simulations also showed the asymmetric shape of the heliosphere and that the **ISMF pressure** reaches its **maximum** at **the quasi-perpendicular direction to the undisturbed direction** of the LISM magnetic field [4].

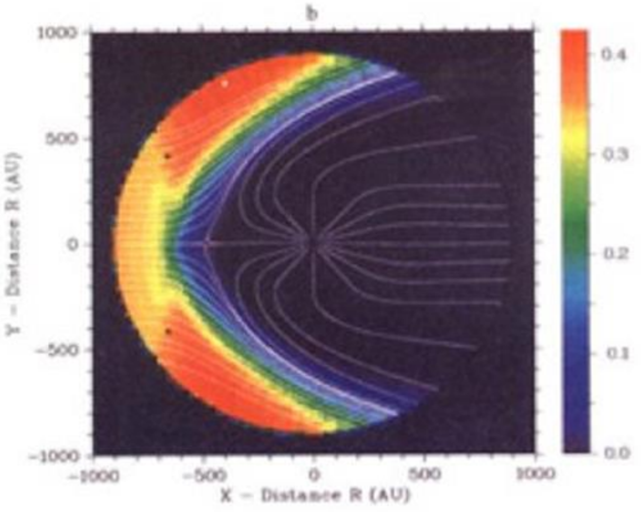
R. Ratkiewicz, A. Barnes and J.R. Spreiter
Local interstellar medium and modeling the heliosphere
JGR, 105, pp. 25021-25032, 2000



B ⊥ V



B ∠ V



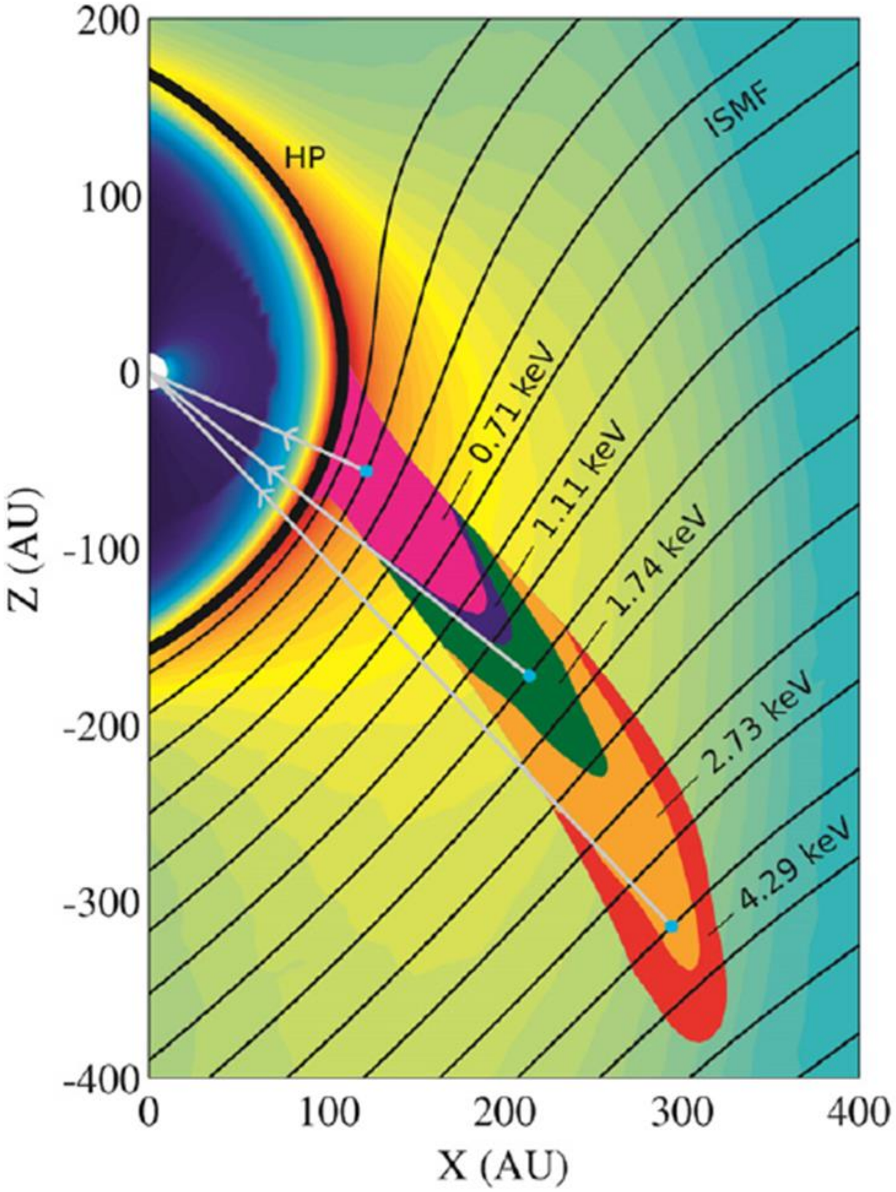
B II V

Magnetic field pressure for perpendicular, oblique and parallel ISMF. The ISMF pressure reaches its maximum in the quasi-perpendicular direction to the unperturbed LISM magnetic field direction

Moreover the **ISMF pressure** reaches **a maximum in the direction exactly perpendicular to draped around HP, lines ISMF** as shown at Fig. 1 by Zirnstein et al. [5].

E.J. Zirnstein, J. Heerikhuisen, H.O. Funsten, G. Livadiotis, D.J. McComas, N.V. Pogorelov
Local Interstellar Magnetic Field Determined from the Interstellar Boundary Explorer Ribbon

ApJL, 818, L18, 6 pp., 2016



Isocontours of the ribbon ENA production rate outside the HP denoted by five colors distinguishing the ENA energies.
The background colors represents the magnetic field magnitude, with some ISMF lines (black curves). Suprathermal ions outside the HP become neutralized by chargé-exchange (blue circles) and form ENAs that may travel back toward IBEX (grey lines).
Note that the "tongue" is set toward the ISMF maxima on each line. This Figure confirms the remark from the former slide.

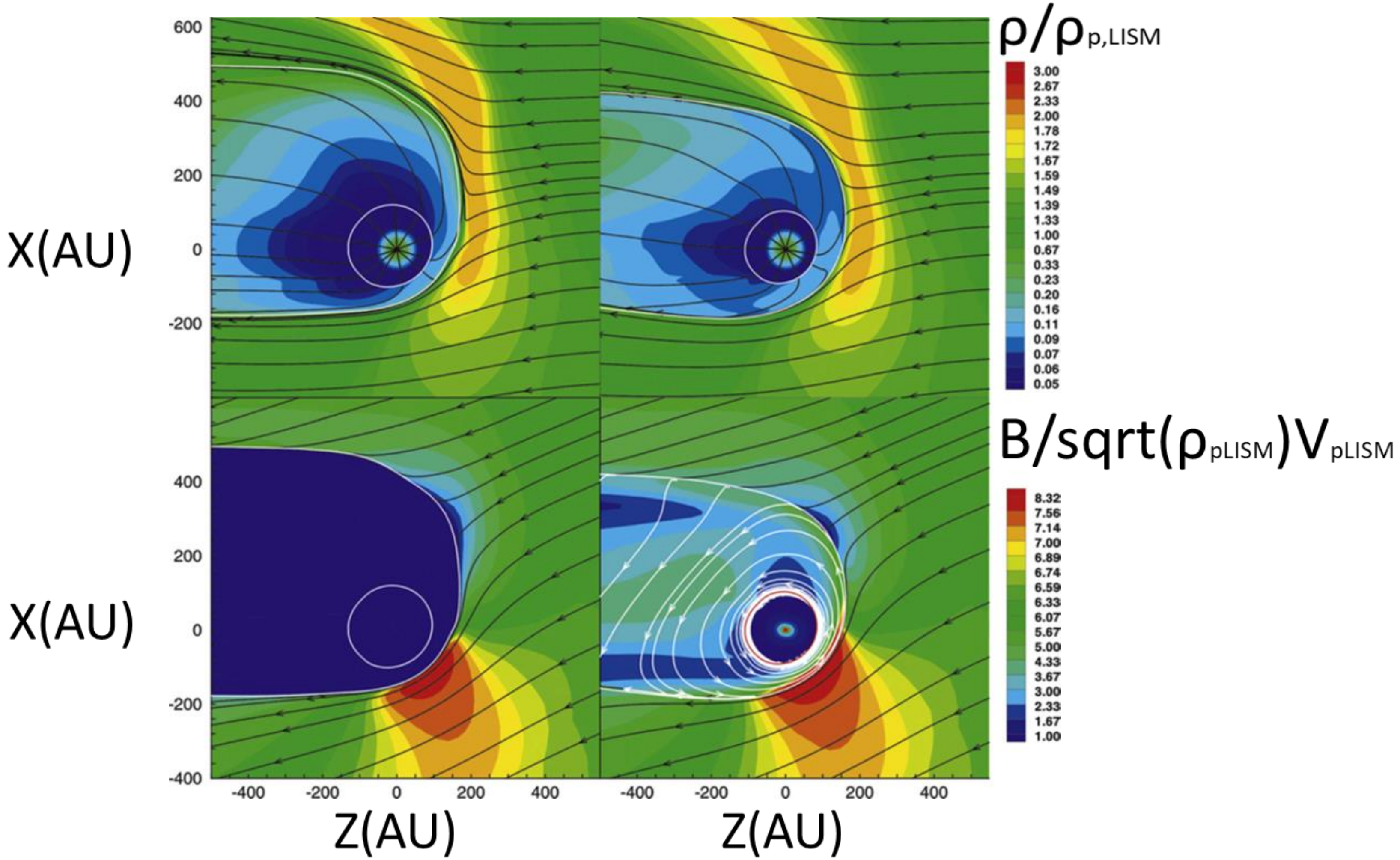


Figure 3. Upper panels: plasma streamlines and isolines of the plasma density normalized to the proton density in LISM. Bottom panels: magnetic field lines and isolines of the magnetic field magnitude in dimensionless units. Left panels correspond to model without HMF, right panels correspond to model with HMF. All of the panels are made in the ZX plane determined by the interstellar velocity and magnetic field vectors.

Conclusion 2

The answer to the second question is positive.

The absolute maximum of ISMF pressure is reached at the area just behind the HP. The „nose" of the HP deviates from the flow direction of the LISM in a direction perpendicular to this ISMF line located at the HP point closest to the Sun.

Perspective
In the light of our knowledge today, „the following science questions (top-level) on the nature of the heliosphere remain open:

- *How are galactic cosmic rays modulated in the heliosphere?*
- *What pressure components uphold the heliosphere boundary?*
- *Does the heliosphere have an open or closed tail?*
- *How is interstellar dust filtered through the interaction region at the heliosphere boundary?*
- *How do shock waves propagate through the heliospheric boundary, and what is their role in particle acceleration?*
- *What is the structure of the hydrogen wall, and how does it relate to similar structures in other astrospheres?*
- *What are the properties of the local interstellar medium?"*

Provornikova et al. White Paper 4060

Thank you for your attention!