«Blowing in the wind», Quy Nhon, August 9, 2016

Stellar and interstellar magnetic field effects on the global structure of astrospheres

Vladislav Izmodenov

(1) Space Research Institute (IKI) Russian Academy of Sciences

(2) Lomonosov Moscow State University, Russia

Collaborators:

Dmitry Alexashov,
Evgeny Golikov

Motivation

Main research topic of our group is the global heliosphere (i.e. interaction of the solar wind with ISM).

It has been shown (for the heliosphere) that both the interstellar and heliospheric magnetic fields play essential role in the global shape of the heliosphere. Both are essentially needed to understand the recent Voyager ½ and IBEX data.

The most of difficulties in the modeling of the SW/LISM interaction is the multi-component nature and magnetic fields.

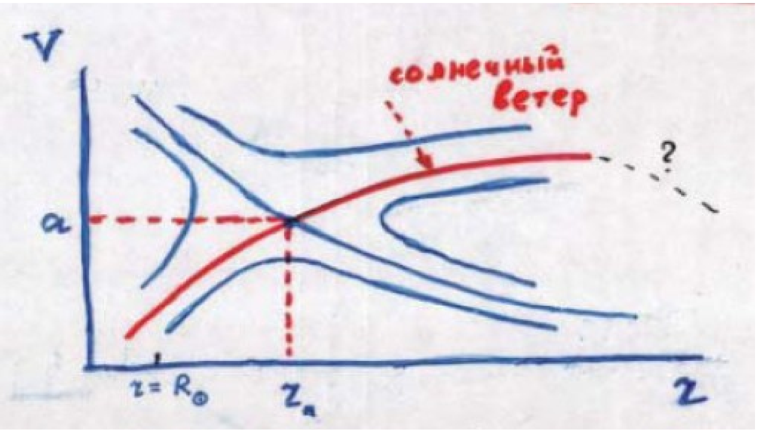
The magnetic field effects should be important for astrospheres of other stars and their observations.

Goal

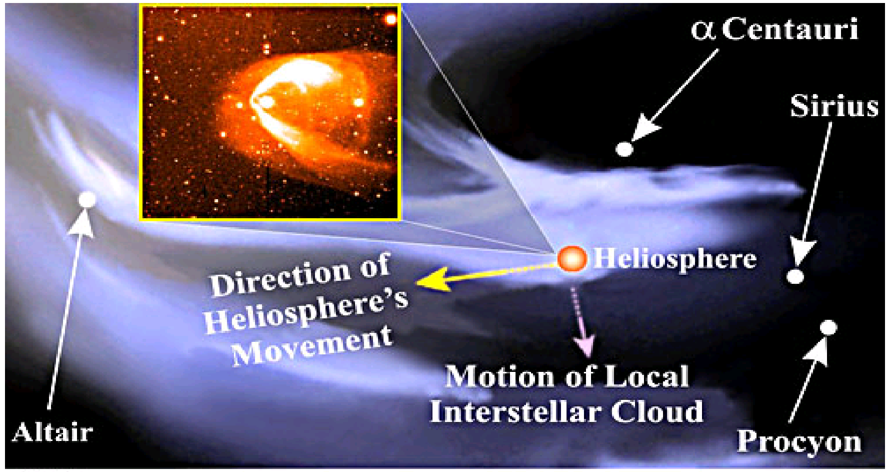
The goal of this talk is to explore the effects of the interstellar and stellar magnetic fields for a «general» astrosphere

Scheme of the flow (gasdynamic case)

1. Solar wind is supersonic M ~ 10



2. Sun moves in LISM with ~25 km/s, M ~ 2



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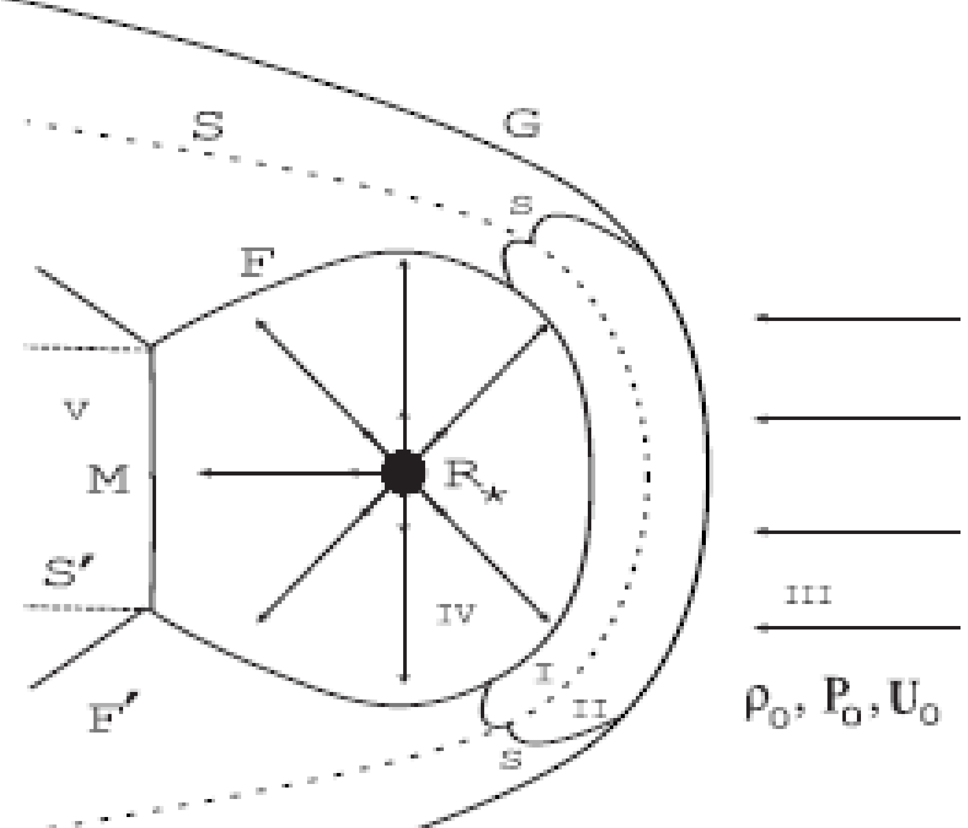


F - stellar (or solar) wind termination shock (TS);

S - contact/tangential discontinuity that separates stellar wind from interstellar medium;

G — bow shock at which the interstellar flow decelerates from supersonic to subsonic. It may disappear for subsonic case and for strong interstellar magnetic field.

Part 1. Interstellar magnetic field (IsMF) effects

Mathematical formulation of the problem

$$\nabla(\rho \boldsymbol{v}) = 0,$$

$$(\boldsymbol{v}\nabla)\boldsymbol{v} = -\frac{\nabla p}{\rho} - \frac{[\boldsymbol{B} rot \boldsymbol{B}]}{4\pi\rho},$$

$$\frac{p}{\rho^\gamma} = const,$$

$$rot[\boldsymbol{v}\boldsymbol{B}] = 0,$$

$$\nabla \boldsymbol{B} = 0,$$

MHD equations

+

Boundary conditions:

- for the stellar wind: (1) stellar mass loss rate $\dot{M}$, (2) terminal velocity V_S, (3) stellar wind pressure: $p_s r^{2\gamma}_s$

In the ISM: (4) $\boldsymbol{v}_\infty$, (5) p_∞, (6) ρ_∞, (7) $\boldsymbol{B}_\infty$

Dimensionless parameters of the problem:

$$K = \frac{\rho_s V_s^2}{\rho_\infty V_\infty^2}, \chi = \frac{V_s}{V_\infty}, M_s = \frac{V_s}{\sqrt{\gamma p_s/\rho_s}}, M_\infty = \frac{V_\infty}{\sqrt{\gamma p_\infty/\rho_\infty}}, A_\infty = \frac{V_\infty\sqrt{4\pi\rho_\infty}}{B_\infty}, \quad \boldsymbol{\alpha}$$

$$M_{+\infty} = 2\left[\sqrt{\frac{1}{A_\infty^2} + \frac{1}{M_\infty^2} + \frac{2cos\alpha}{A_\infty M_\infty}} + \sqrt{\frac{1}{A_\infty^2} + \frac{1}{M_\infty^2} - \frac{2cos\alpha}{A_\infty M_\infty}}\right]^{-1}, \quad \gamma$$

where $V = |\boldsymbol{v}|$, $B = |\boldsymbol{B}|$ and α is the angle between $\boldsymbol{v}_\infty$ and $\boldsymbol{B}_\infty$.

1. If *Ms>>1 => hypersonic solar/stellar wind => no dependence on Ms*

2. It is easy to show that geometrical pattern does not depend on $\chi = \frac{V_s}{V_\infty}$
   Density and velocity are recalculated: $\tilde{v}_2 = n v_2, \quad \tilde{p}_2 = p_2, \quad \tilde{\rho}_2 = n^{-2}\rho_2$

This allows us to reduce fluctuations at the contact discontinuity and allows to get initial condition to study K-H instability.

3. For K>>1 distances are proportional to $\sqrt{K}$

Therefore, the solution depends on M_∞, γ, $\boxed{A_\infty,\ M_{+\infty}\ (\text{or } \alpha)}$,

Numerical scheme

- Godunov solver in the case of gas-dynamics;
- HLLD scheme for MHD (exact MHD solver is in preparation);
- Limiter: Chakravarthy-Osher

$$\phi_j = \frac{1-\theta}{2}\mathrm{minmod}(1, \beta\hat{\theta}_j) + \frac{1+\theta}{2}\mathrm{minmod}(\hat{\theta}_j, \beta), \quad 1 \le \beta \le \frac{3-\theta}{1-\theta}$$

Here the parameter θ defines the order approximation of the scheme. If θ=1/2 and 1/3 the scheme has the second and third order of approximation. When the β increase, then the number of cells, where the scheme turns to the first the order approximation decrises.

- Modification of the original Godunov algorithm of

the computational node reconstruction in the vicinity of the contact discontinuity for supersonic flow.

It reduces numerical instability! Physical reason is clear in this case!

- Charge-exchange with H atoms helps to stabilize the flow (acts as an effective viscosity).

Computational grid

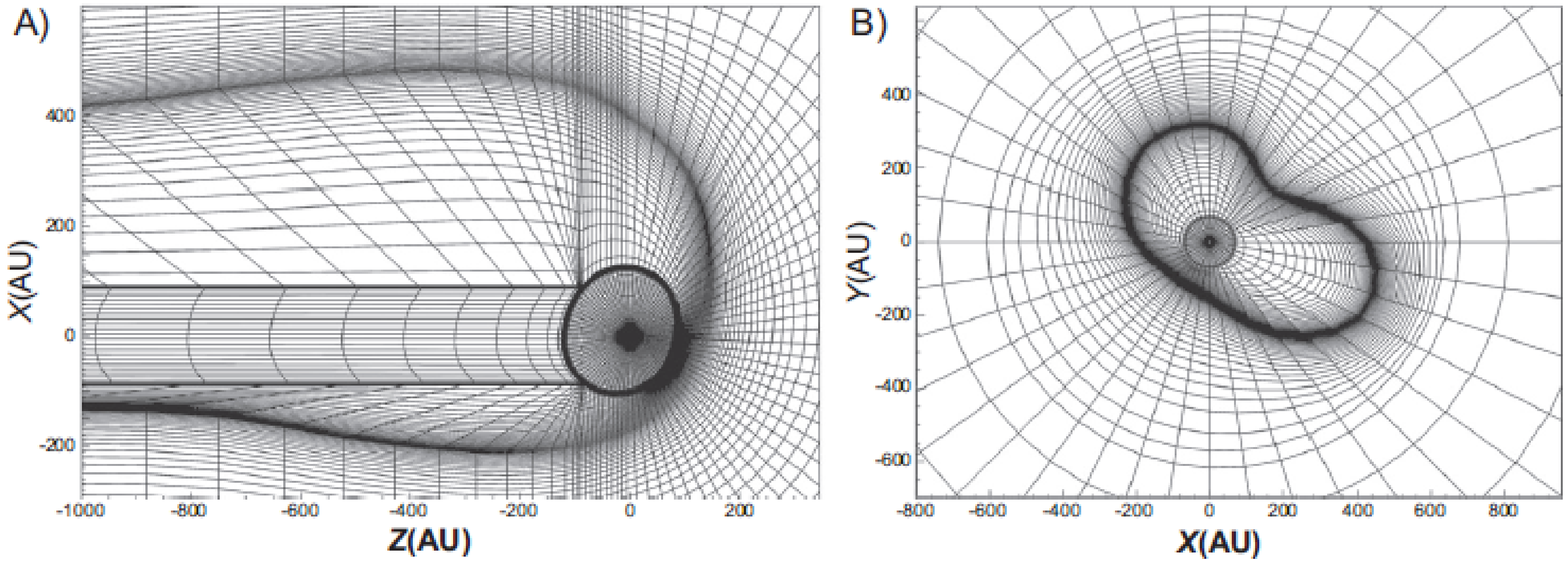
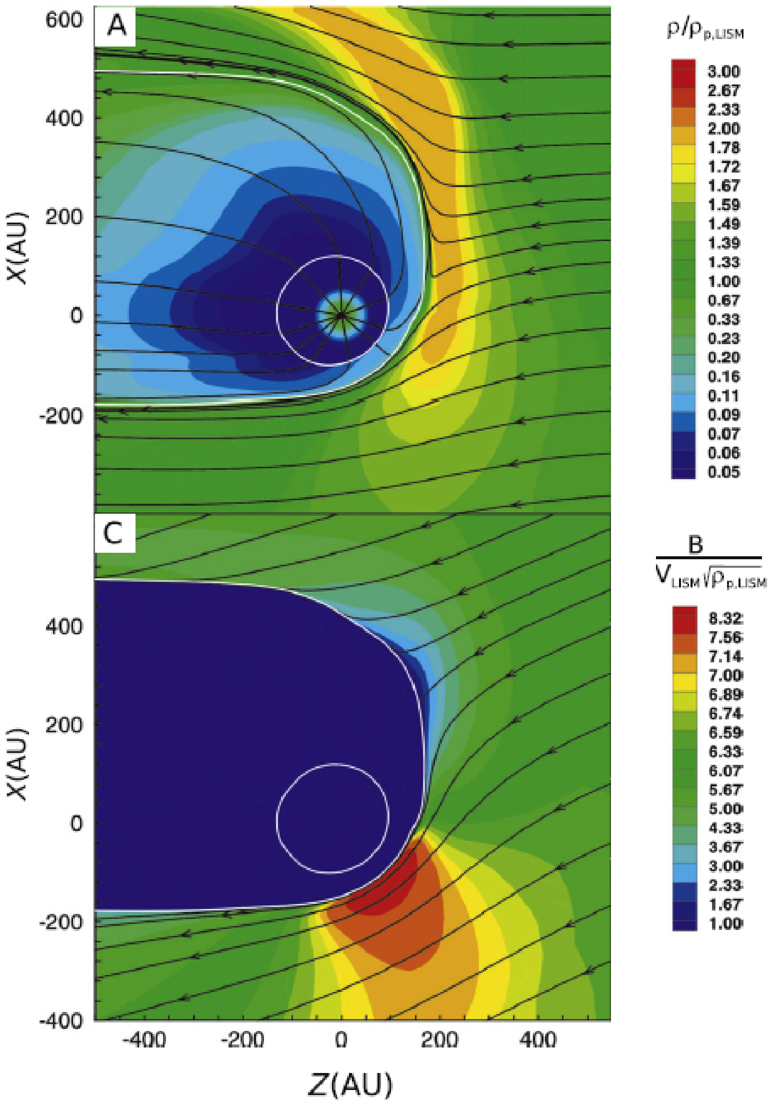


Figure 2. Demonstration of the computational grid in the *ZX* plane (panel (A)) and in the plane parallel to the *XY* plane at $z = -500$ AU (panel (B)).

Izmodenov and Alexashov, ApJS 2015

(1) IsMF creates strong assymetries of the global shape



From Izmodenov et al, ApJS, 2015

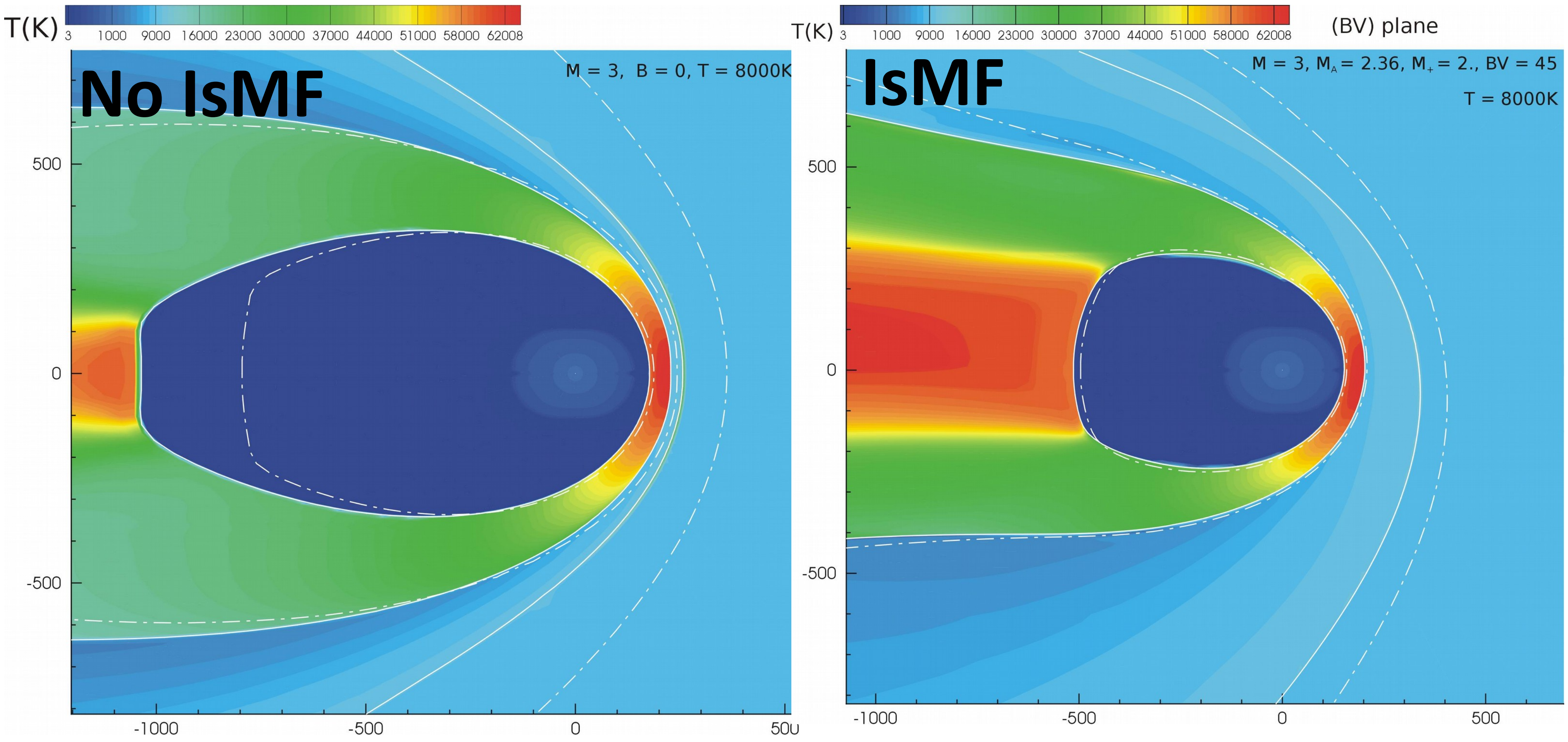
$B_\infty = 4.4\ \mu G,\ \alpha = 20^o$

Strongly assymetric astrosphere

No Bow shock

Izmodenov, Alexashov, Myasnikov, A&A 2005;
McComas et al, Nature, 2014

(2) IsMF reduces the effects of radiative cooling

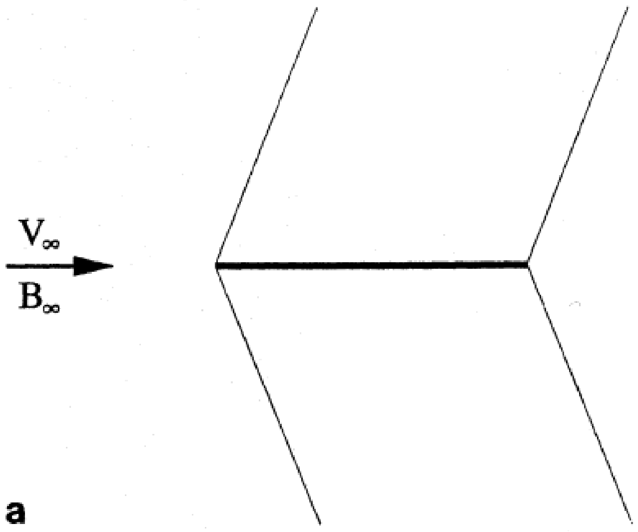


Solid curves: radiative cooling;
Dashed curves: no radiative cooling.

(3) Opens (theoretical) possbility to observe inclusion shocks in quasi-hyperbolic regime

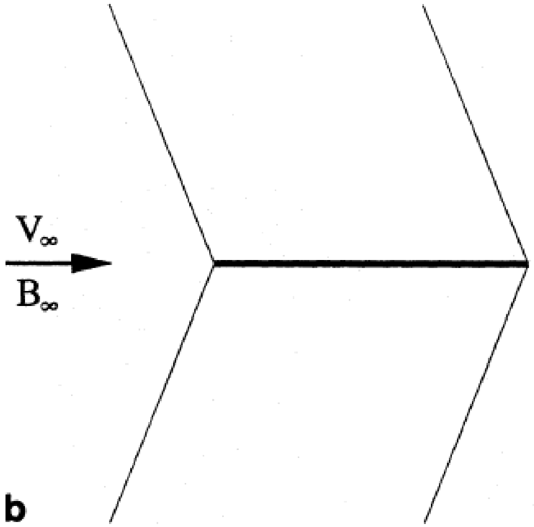
-

Hyperbolic regime



$$V_\infty > a_+$$

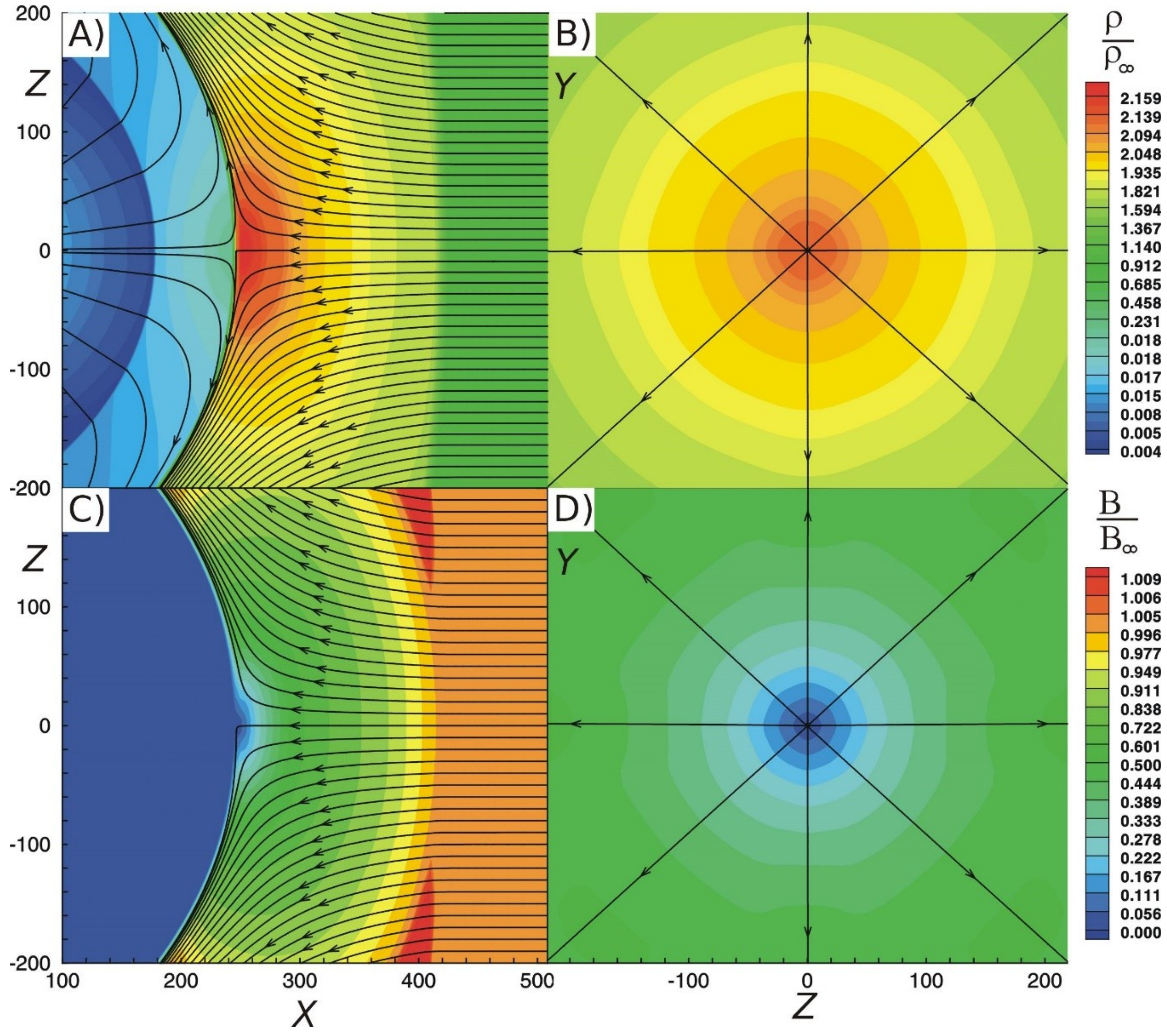
Quasi-hyperbolic regime



$$a_0 a_A / \sqrt{a_0^2 + a_A^2} < V_\infty < a_-$$

Baranov and Zaitsev (1995)

B|| V – regular flow



$$A_\infty = 1.773$$

3D MHD model (B|| V)

$K = 32980,\ M_s = 10,\ B_s = 0$ and $M_\infty = 1.5.$

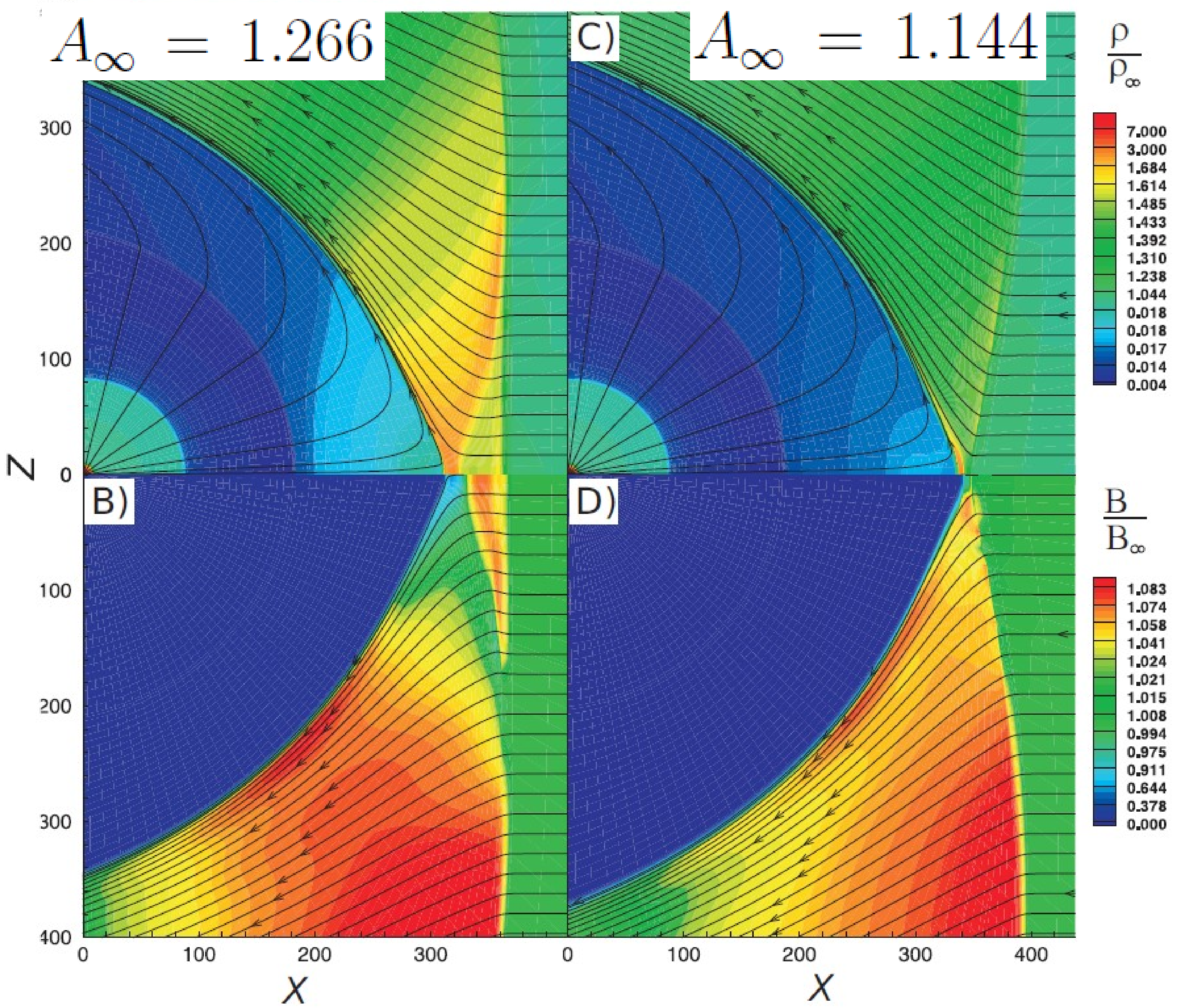
Range when inclusion shock wave is possible:

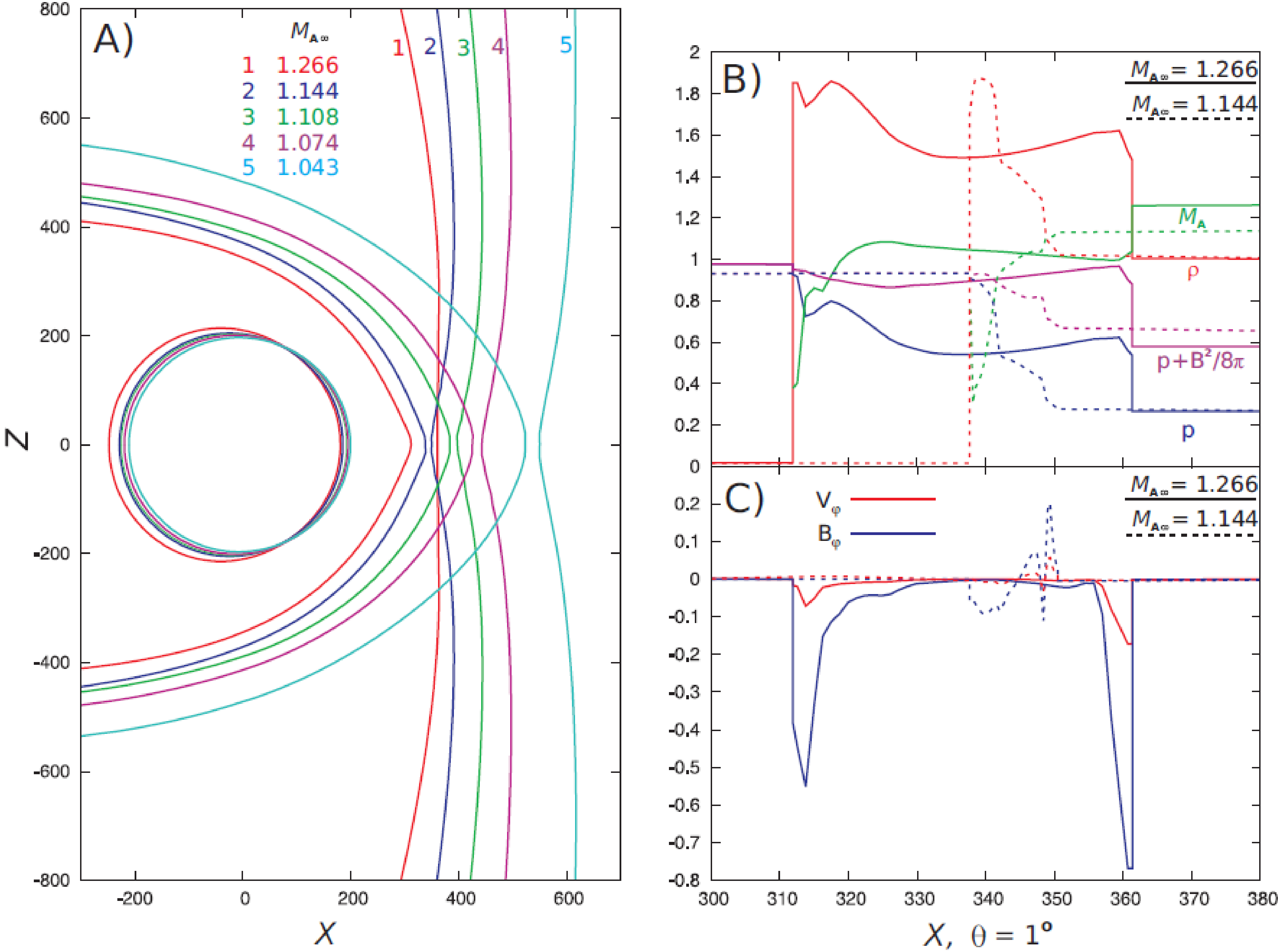
$$1 < A_\infty < \sqrt{\frac{(\gamma+1)M_\infty^2}{2+(\gamma-1)M_\infty^2}}$$

(Kulikovski et al. 2001)

Shape of the shock is determined by the non-monotonic behavior of the function:

$$M_{\theta\infty} = M_{+\infty}(\alpha = \theta)/cos\theta$$



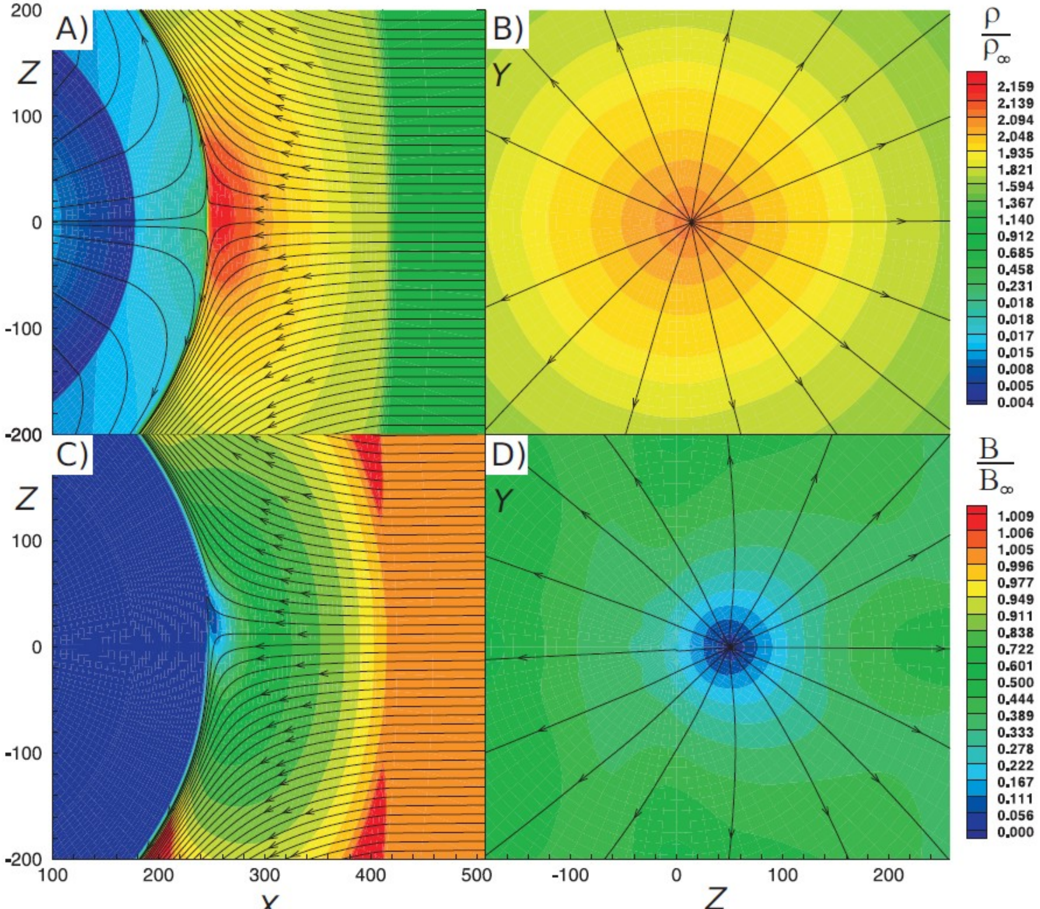


A)
$M_{A\infty}$
1 1.266
2 1.144
3 1.108
4 1.074
5 1.043
Z
X
B)
$M_{A\infty}$ = 1.266
$M_{A\infty}$ = 1.144
M_A
ρ
$p+B^2/8\pi$
p
C)
V_φ
B_φ
$M_{A\infty}$ = 1.266
$M_{A\infty}$ = 1.144
X, θ = 1°

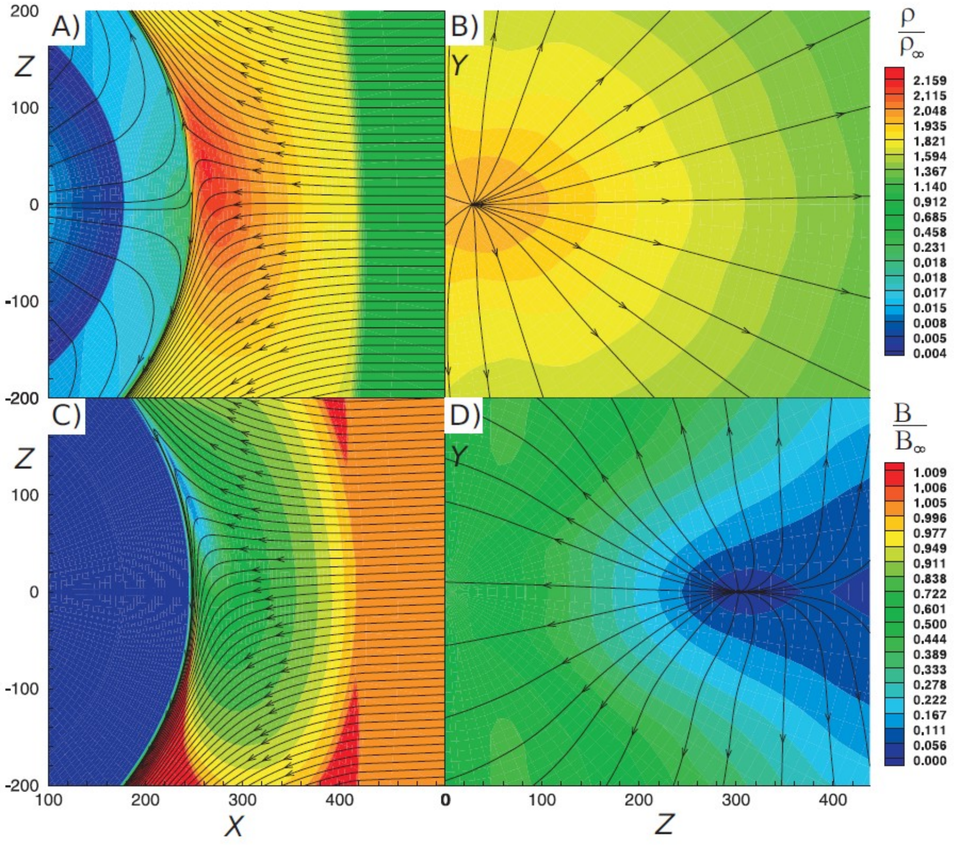
3D Regular flow pattern – small angle between B and V

$$A_\infty = 1.773$$

$$\angle(\boldsymbol{B}_\infty, \boldsymbol{v}_\infty) = 0.57^\circ$$



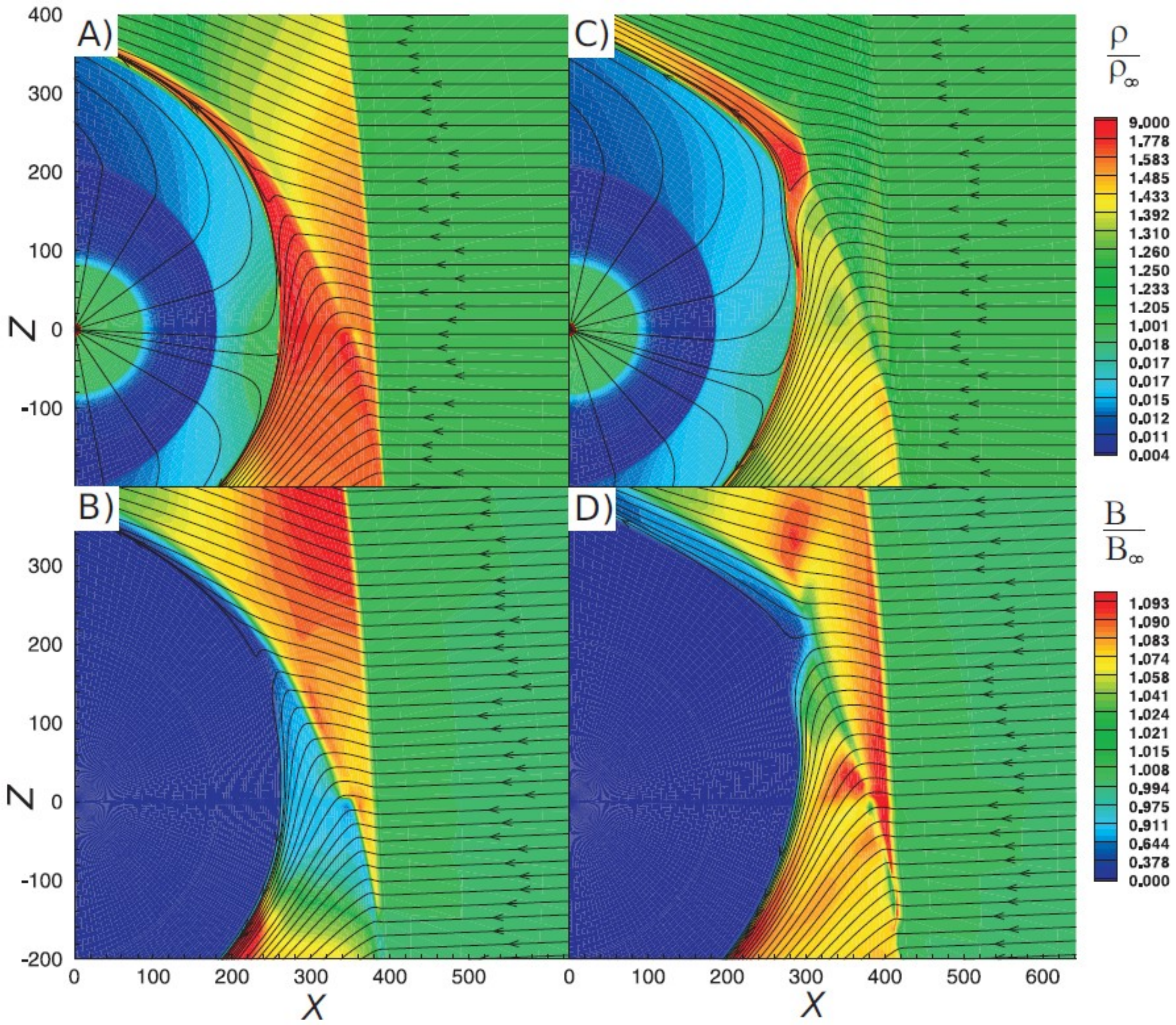
$$\angle(\boldsymbol{B}_\infty, \boldsymbol{v}_\infty) = 2.29^\circ$$



$$\angle(\boldsymbol{B}_\infty, \boldsymbol{v}_\infty) = 2.29^\circ$$

MHD flow with inclusion shock wave

$A_\infty = 1.266$ $\quad$ $A_\infty = 1.144$



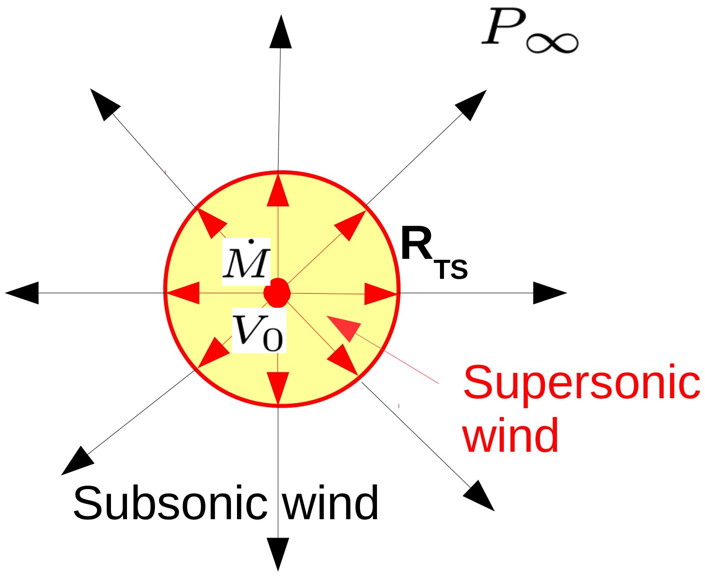
Conclusions (part 1 — interstellar magnetic field effects):

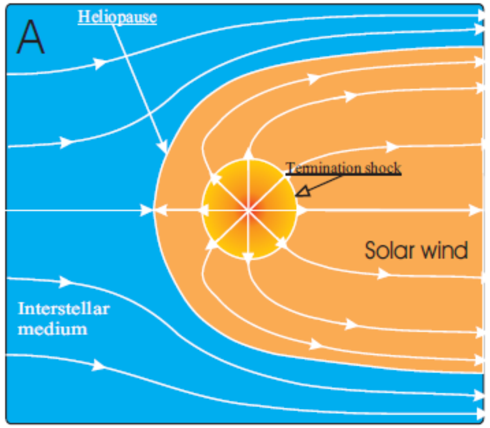
- inclined (with respect of interstellar flow) magnetic field produces assymetries in the global shape of the astrospheres => observed asymmetries in astrospheres may allow to estimate interstellar magnetic field;
- the bow shocks are absent for the most asymetric astrospheres with strong interstellar magnetic field;
- magnetic field reduces the effect of «shrinking» of the shock layer between the BS and astropause;
- astrospheres are possible source where MHD inclusion waves which can probably be discovered.

Part 2 — Effect of stellar azimutal magnetic field

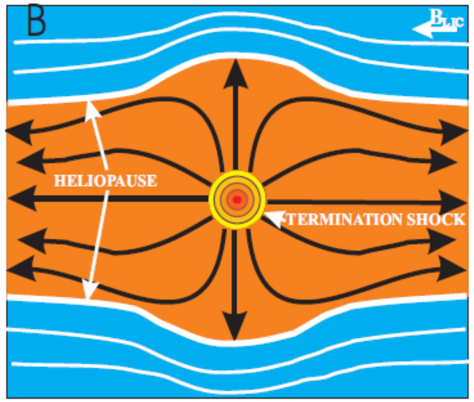
(Golikov et al., MNRAS, 2016)

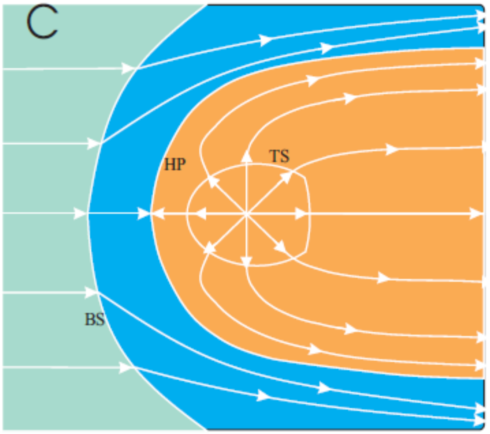
Classical scenaria





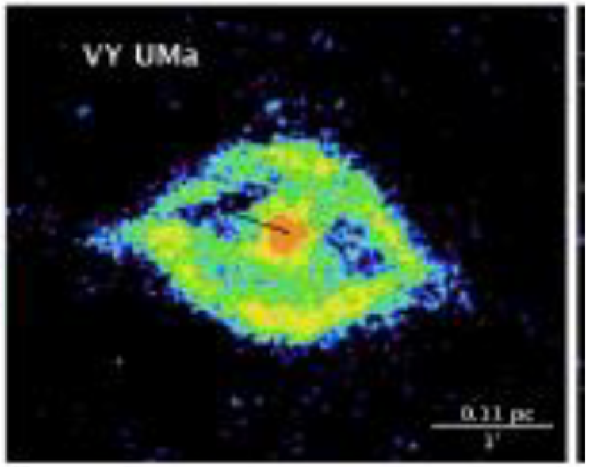
Parker (1961)





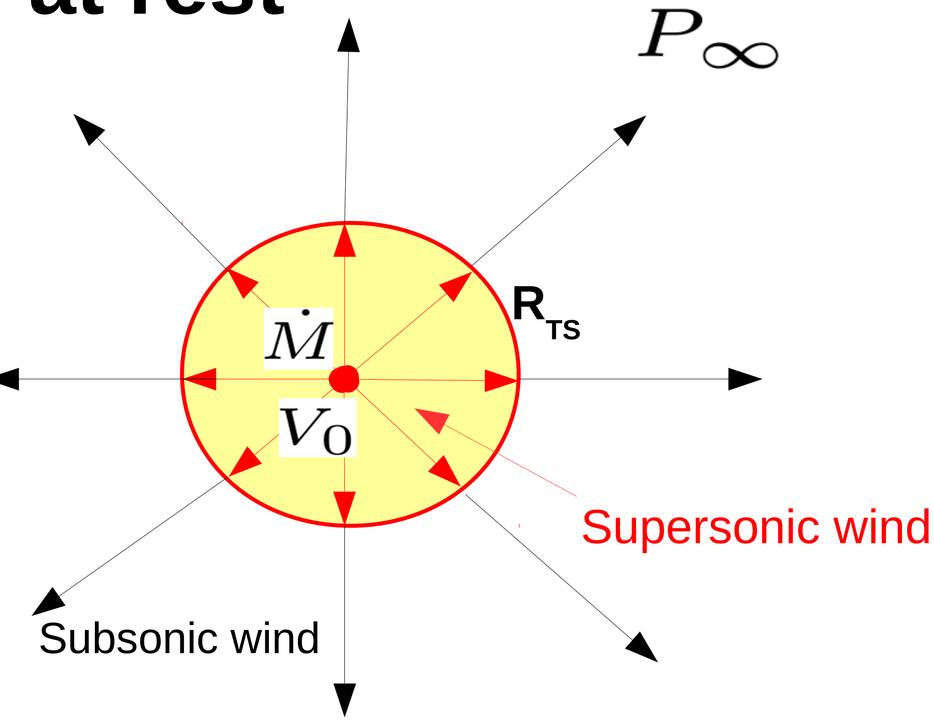
Baranov et al (1970)

Eyes



However,
it seems that
one possibility
has been missed in
classical papers!

Parker model of the hypersonic source in the interstellar gas at rest



Solving: curl [***V*** x ***B***] =0

$$R < R_{TS}: \quad B_R \sim 1/R^2$$

$$B_\phi \sim (1/R)\sin\theta$$

$$B_\theta = 0$$

$$R > R_{TS}: \quad B_\phi \sim R\sin\theta$$

$$B_\theta = 0$$

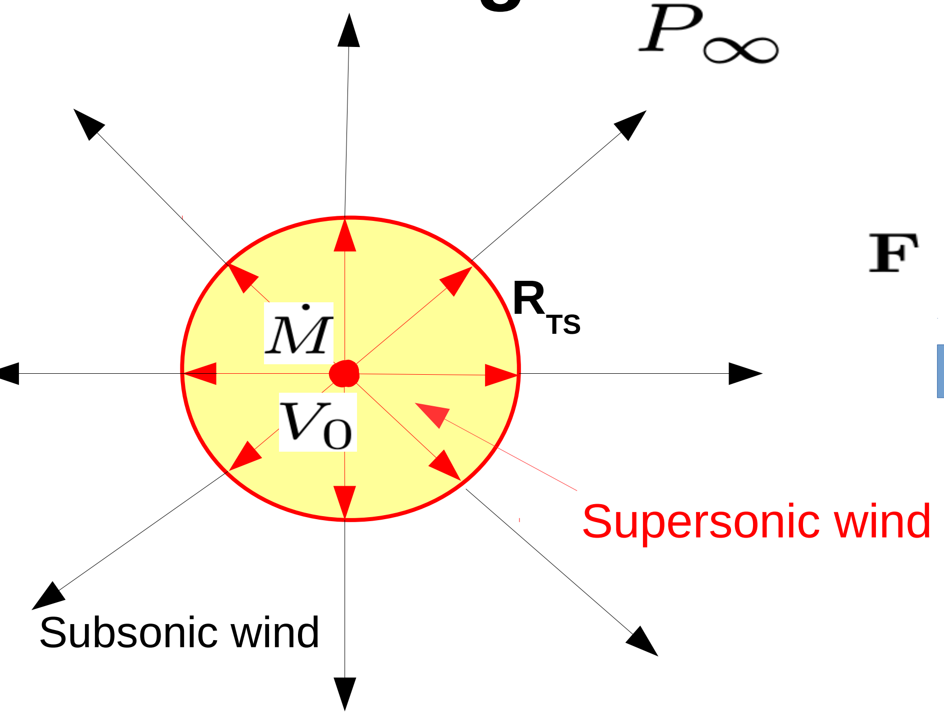
$$R_{TS} = \sqrt{\frac{\dot{M}V_0}{P_\infty}}$$

Magnetic field increases in the subsonic wind

$$\mathbf{F} = rot\mathbf{B}\times\mathbf{B}$$

- magnetic field deflects the solar wind toward the axis of rotation

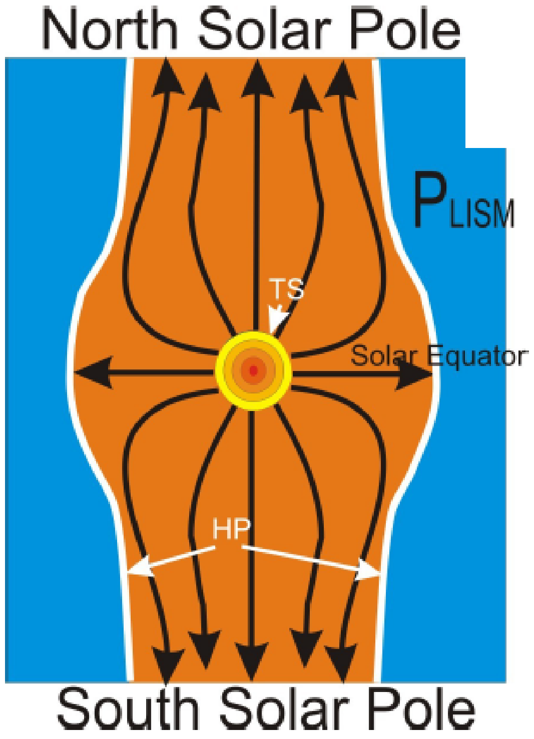
Parker model of the hypersonic source in the interstellar gas at rest



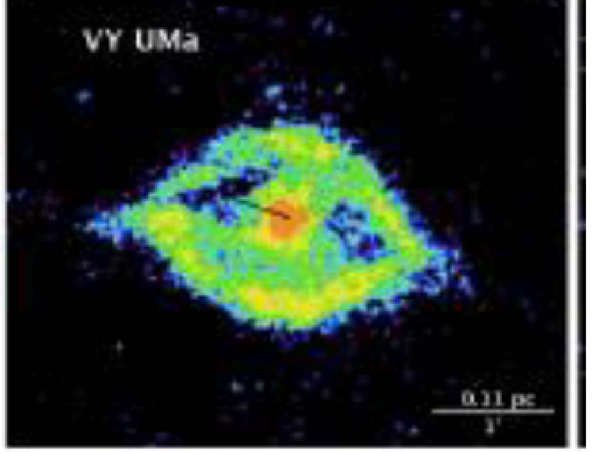
$$R_{TS} = \sqrt{\frac{\dot{M} V_0}{P_\infty}}$$

$$\mathbf{F} = rot\mathbf{B} \times \mathbf{B}$$

The



Eyes



Two-jet structure is formed due to stellar magnetic field (even weak field) !!!

For the heliosphere the two-jet structure suggested by Opher et al. (2015), Drake et al (2015)

Golikov et al., MNRAS, 2016:

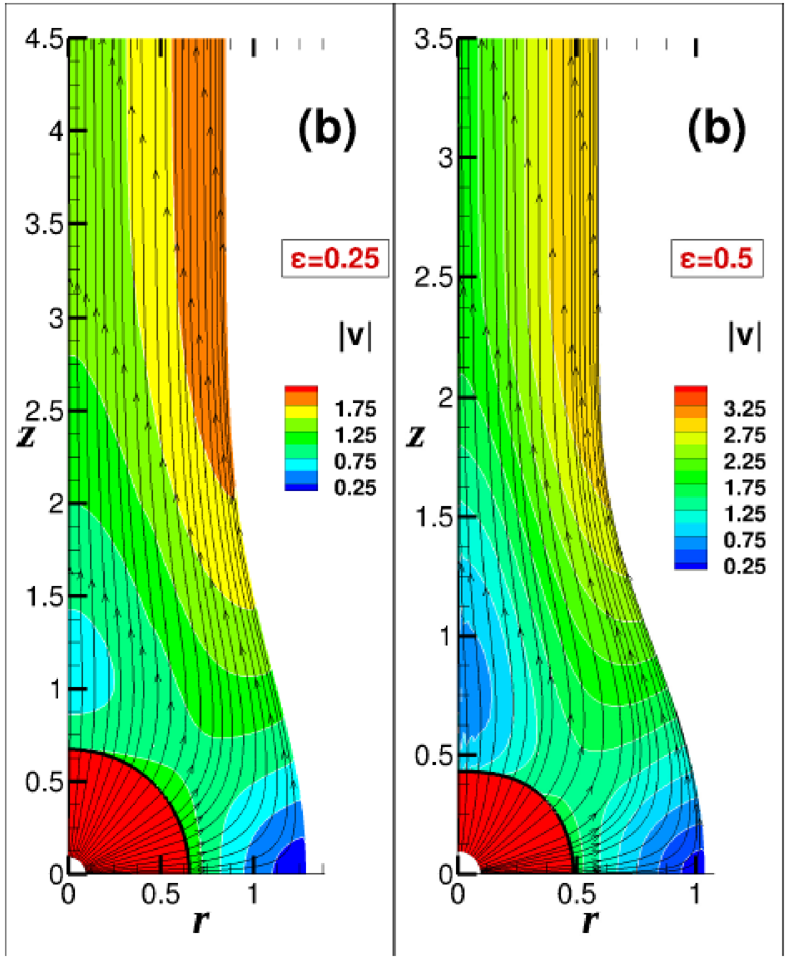
- the problem depends only on one dimensionless parameter:

$$\varepsilon = \frac{B_E}{V_E\sqrt{4\pi\rho_E}} = \frac{1}{M_{A,E}}$$

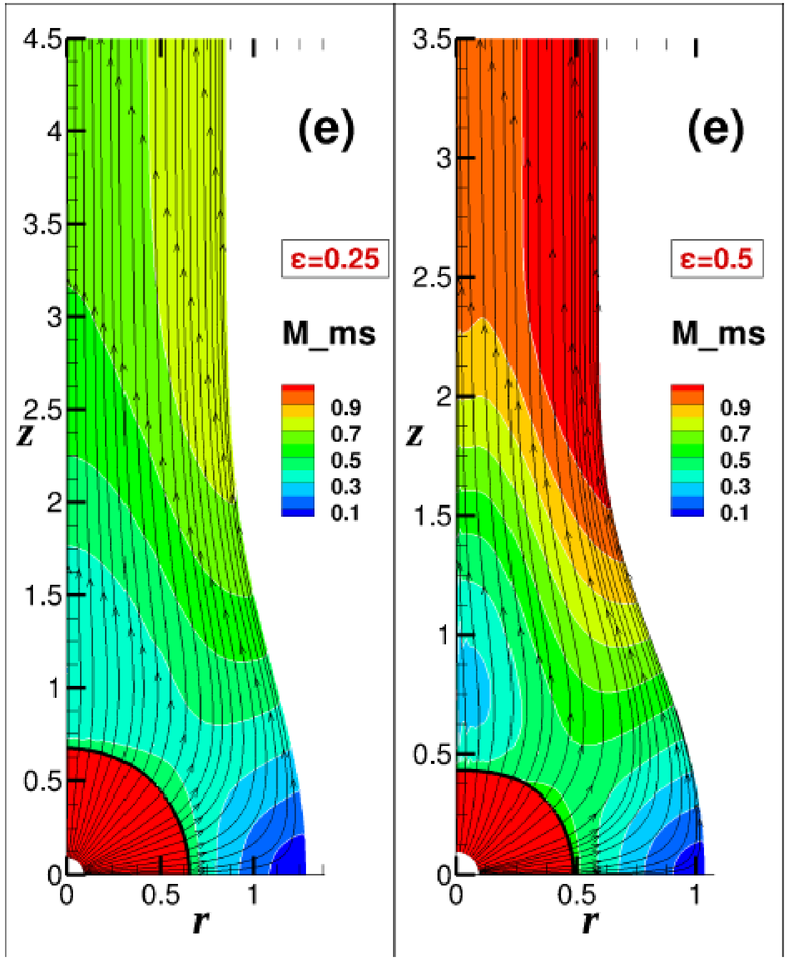
- parametrical numerical solution has been performed;
- three first integrals of MHD eq. has been obtained;
- distributions in the jets have been obtained (solving ODE);
- it has been shown that the stellar magnetic field can be estimated from geometric pattern

Numerical results: $\varepsilon = 0.25$ and $\varepsilon = 0.5$

Velocity



Fast-magnetosonic Mach number



Conclusions

<u>Part 1 — interstellar magnetic field effects:</u>

- inclined (with respect of interstellar flow) magnetic field produces assymetries in the global shape of the astrospheres => observed asymmetries in astrospheres may allow to estimate interstellar magnetic field;
- the bow shocks are absent for the most asymetric astrospheres with strong interstellar magnetic field;
- magnetic field reduces the effect of «shrinking» of the shock layer between the BS and astropause;
- astrospheres are possible source where MHD inclusion waves which can probably be discovered.

<u>Part 2 — stellar magnetic field effects:</u>

- **stellar magnetic field (even very weak) may significanly change the structure of astrosphere; two-jet structure is formed;**
- **it is possible to infer stellar magnetic field from the geometrical pattern of astrosphere.**

Equations

$$\frac{\partial \rho}{\partial t} + div(\rho \boldsymbol{u}) = q_1, \qquad q_1 = m_{\mathrm{p}} n_{\mathrm{H}} \cdot (\nu_{\mathrm{ph}} + \nu_{\mathrm{impact}}),$$

$$\frac{\partial \rho \boldsymbol{u}}{\partial t} + div(\rho \boldsymbol{u}\boldsymbol{u} + p\hat{I}) = \boldsymbol{q}_2 \qquad q_2 = \int m_{\mathrm{p}}(\nu_{\mathrm{ph}} + \nu_{\mathrm{impact}}) \boldsymbol{v}_{\mathrm{H}} f_{\mathrm{H}}(\boldsymbol{v}_{\mathrm{H}}) d\boldsymbol{v}_{\mathrm{H}} +$$

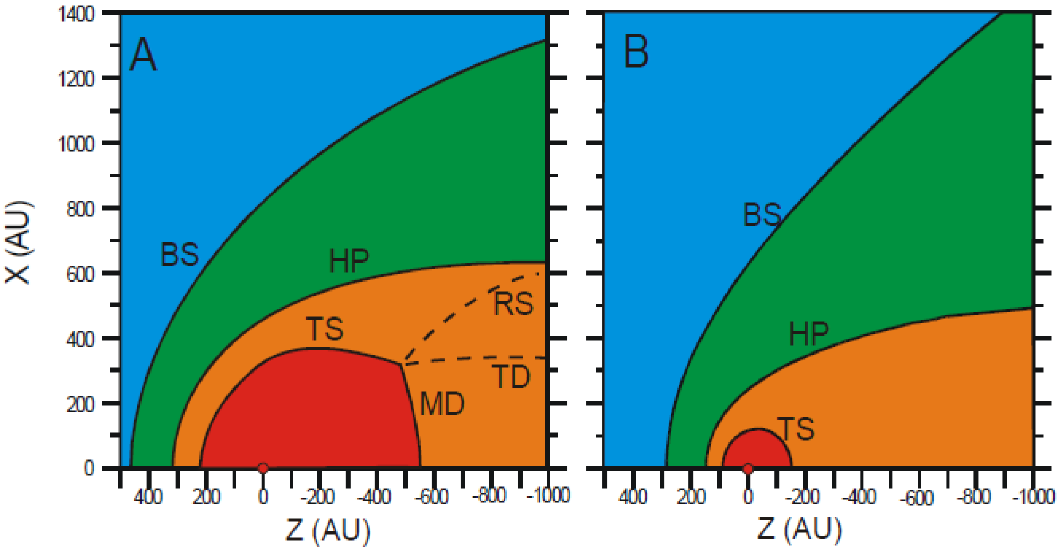
$$\frac{\partial E}{\partial t} + div([E + p]\boldsymbol{u}) = q_3 + q_{3,e} \qquad \int\int m_{\mathrm{p}} v_{\mathrm{rel}} \sigma_{ex}^{HP}(v_{\mathrm{rel}})(\boldsymbol{v}_{\mathrm{H}} - \boldsymbol{v}) f_{\mathrm{H}}(\boldsymbol{v}_{\mathrm{H}}) \sum_{i=p,pui} f_i(\boldsymbol{v}) d\boldsymbol{v}_{\mathrm{H}} d\boldsymbol{v},$$

$$\frac{\partial f_{\mathrm{H}}}{\partial t} + \boldsymbol{v}_{\mathrm{H}} \cdot \frac{\partial f_{\mathrm{H}}}{\partial \boldsymbol{r}} + \frac{\boldsymbol{F}}{m_{\mathrm{H}}} \cdot \frac{\partial f_{\mathrm{H}}}{\partial \boldsymbol{v}_{\mathrm{H}}} = -(\nu_{ph} + \nu_{\mathrm{impact}}) f_{\mathrm{H}}(\boldsymbol{r}, \boldsymbol{v}_{\mathrm{H}})$$

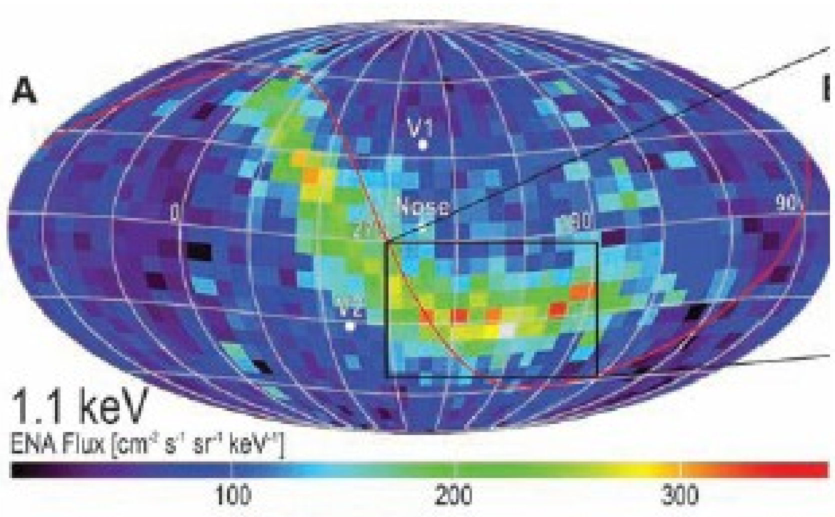
$$-f_{\mathrm{H}} \cdot \sum_{i=p,pui} \int |\boldsymbol{v}_{\mathrm{H}} - \boldsymbol{v}_i| \sigma_{ex}^{\mathrm{HP}} f_i(\boldsymbol{r}, \boldsymbol{v}_i) d\boldsymbol{v}_i$$

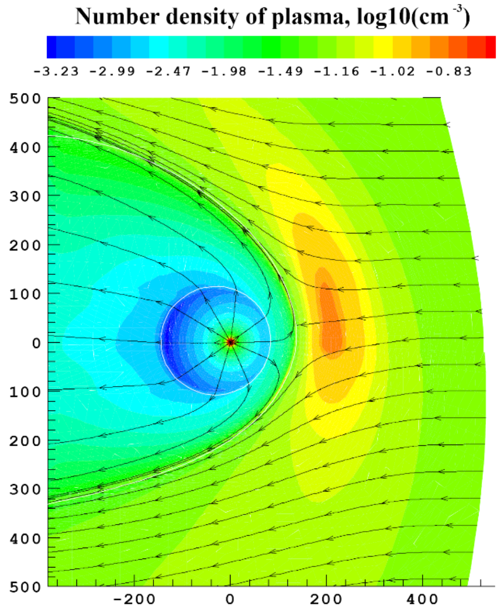
$$+ \sum_{i=p,pui} f_i(\boldsymbol{r}, \boldsymbol{v}_{\mathrm{H}}) \int |\boldsymbol{v}_{\mathrm{H}}^* - \boldsymbol{v}_{\mathrm{H}}| \sigma_{ex}^{\mathrm{HP}} f_{\mathrm{H}}(\boldsymbol{r}, \boldsymbol{v}_{\mathrm{H}}^*) d\boldsymbol{v}_{\mathrm{H}}^*.$$

Examples of interstellar neutral importance in the heliospheric interface (SW/LISM interaction region)



IBEX





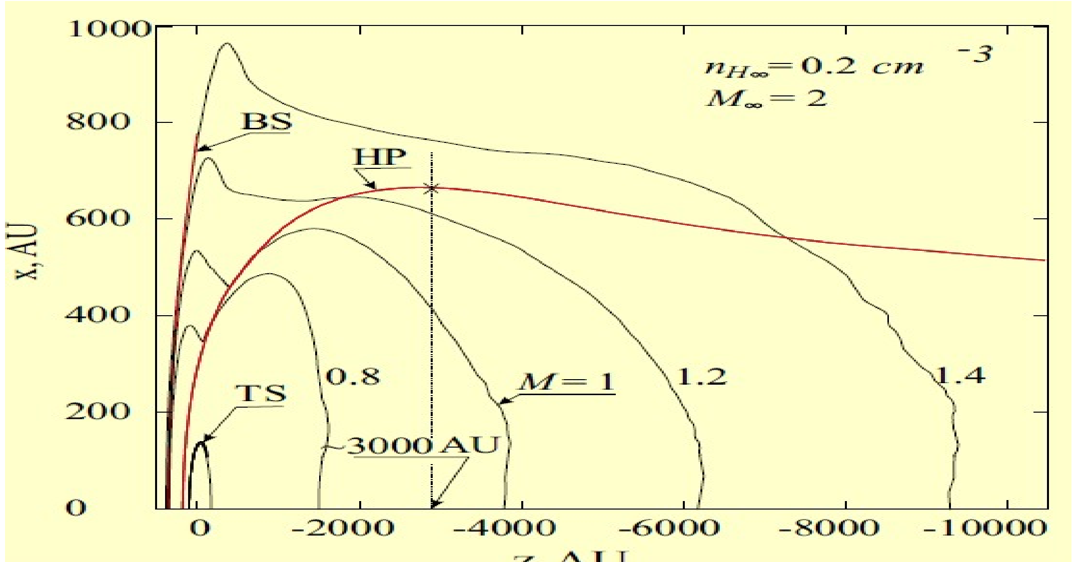


Illustration of K-H instability in the case of wind-wind interaction in binary stars (Myasnikov ~2003)

⇒ No full convergence with increase number of cells. It disappears when a physical dissipative process (e.g.thermal conduction) is added.