Solar wind interaction with Pluto's escaping atmosphere

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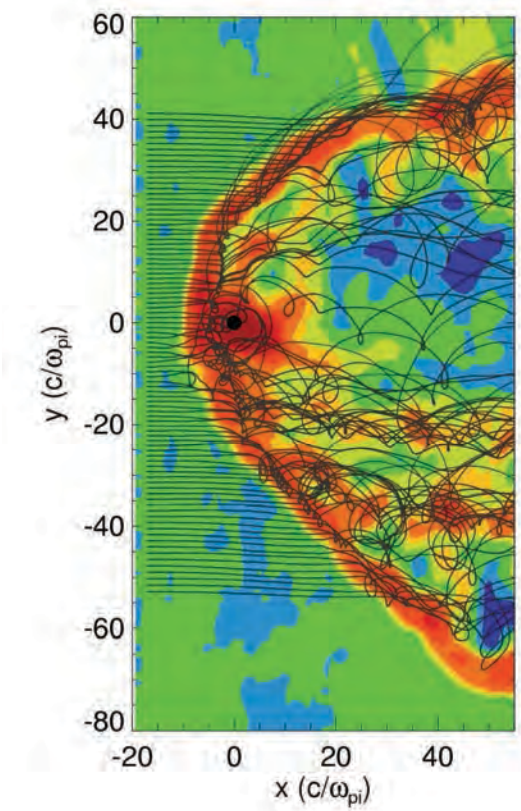
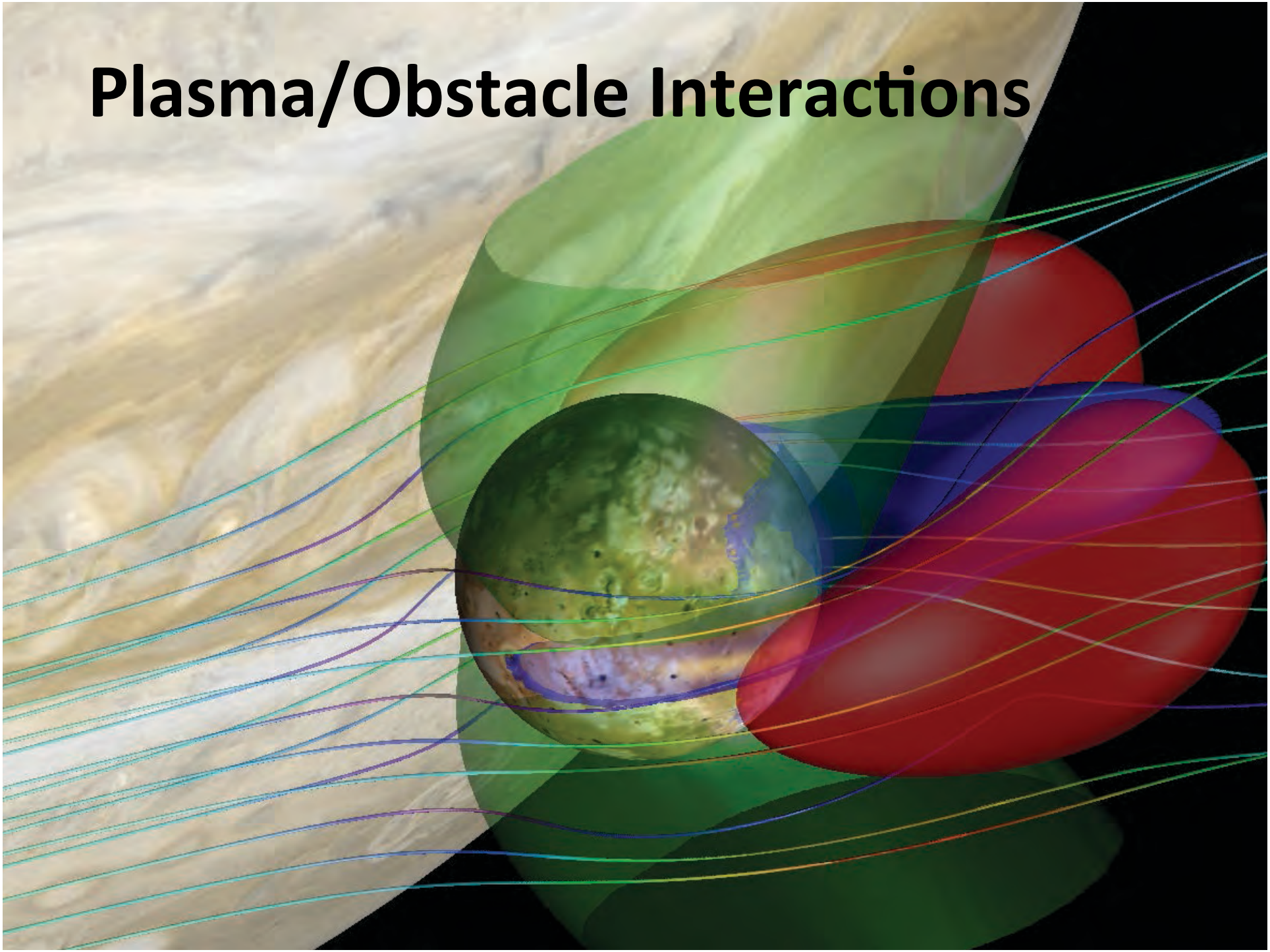
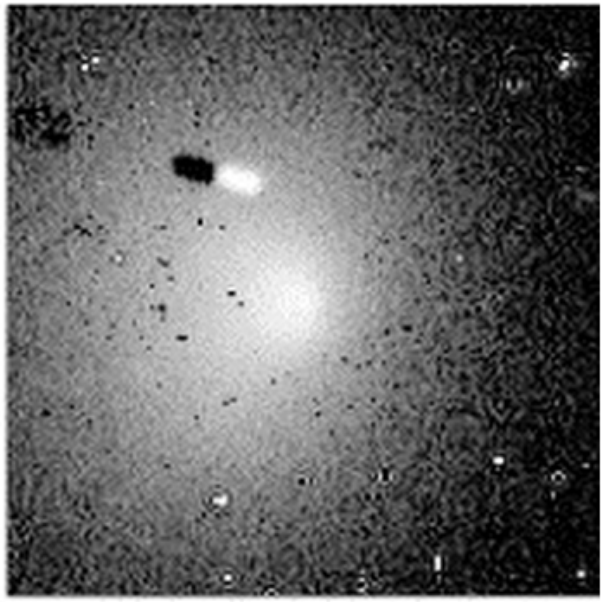


Plasma/Obstacle Interactions

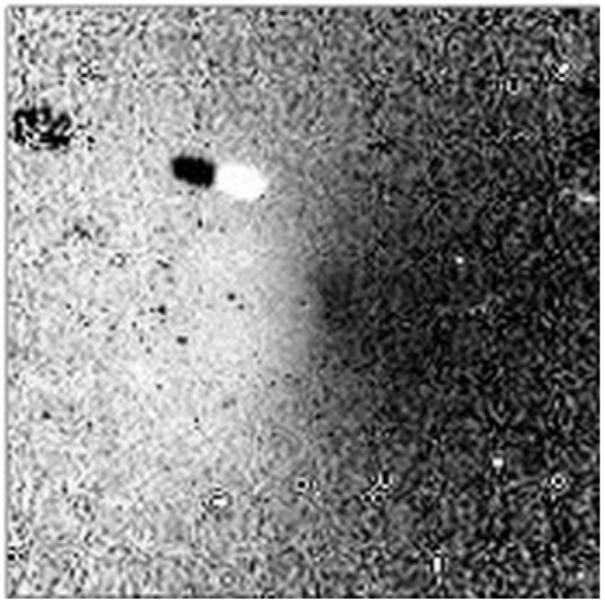


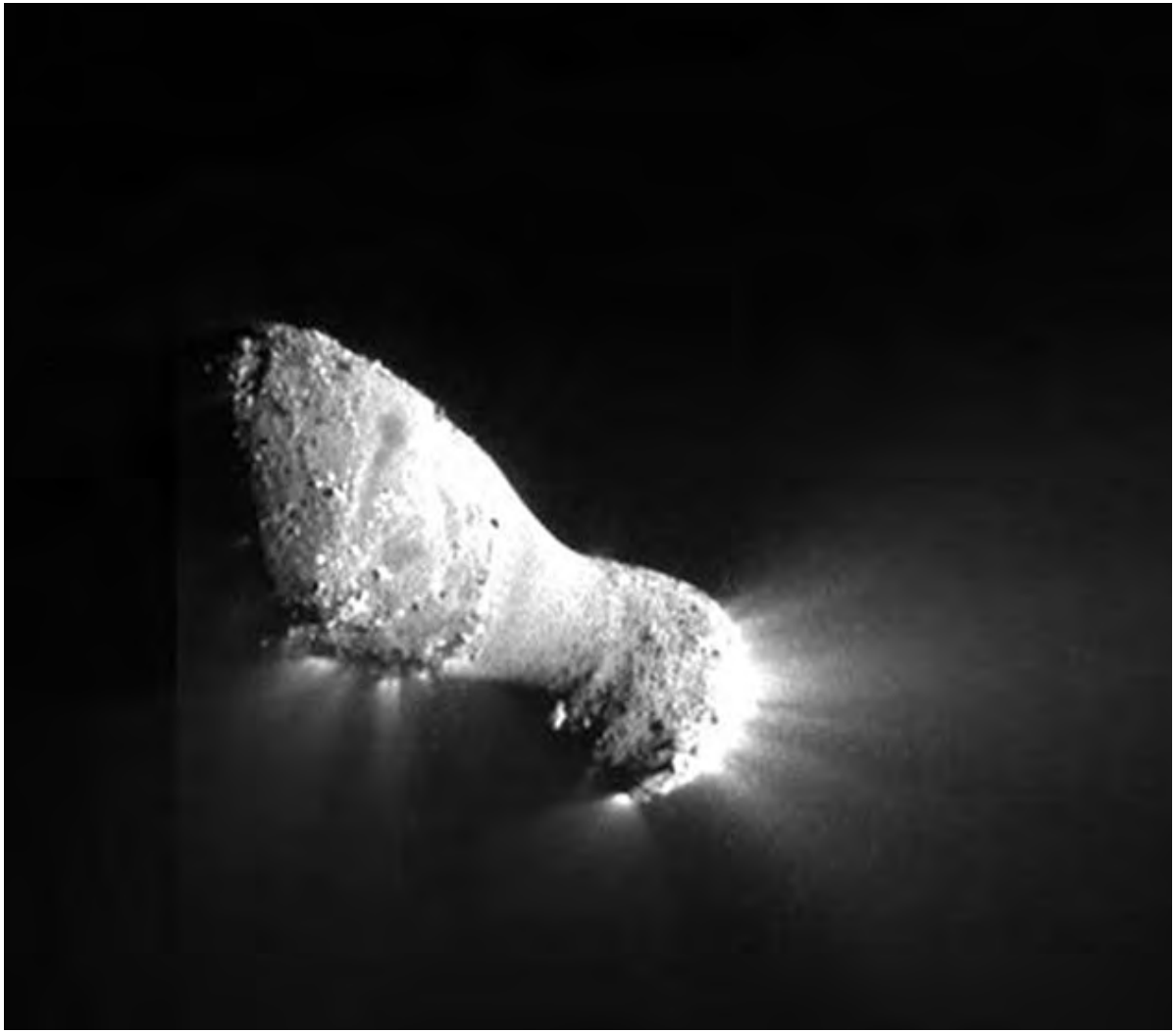
Comets

CN



CN Enhanced





Neutral escape

- Neglect gravity, so no hydrostatic equilibrium
- Essentially an exosphere (mean free path for collisions > scale height)
- Once neutrals escape, u_{esc} = const
- Show

$$n_n(r) = \frac{Q_o}{4\pi u_{esc} r^2}$$

Fate of escaping neutrals

- Photoionization

$$h\nu + \mathrm{H_2O} \rightarrow \mathrm{H_2O^+} + e$$

- Charge exchange

$$\mathrm{H^+} + \mathrm{H_2O} \rightarrow \mathrm{H} + \mathrm{H_2O^+}$$

Ion production rate

- Determined from the cometary ion production rate

$$S_i = \frac{n_n(r)}{\tau}$$

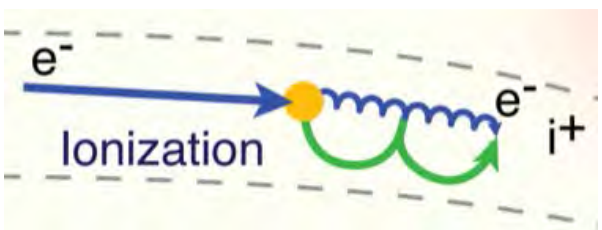
Photoionization timescale

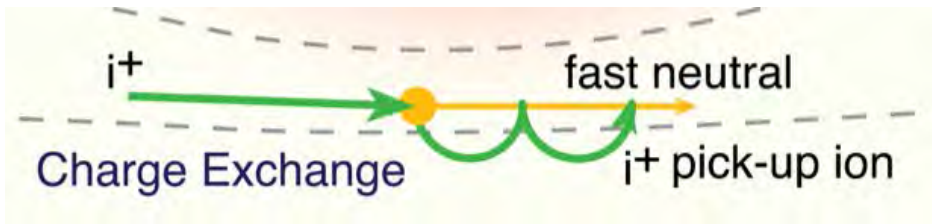
$$\dot{M}_i = \frac{m_i Q_o}{4\pi\tau u_{esc} r^2}$$

Assume neutral density is unaffected by ion production

Mass loading of solar wind flow

- Momentum exchange to “pickup” ions slows down the solar wind.
- Pickup ion distribution critical for understanding the cometary plasma environment.





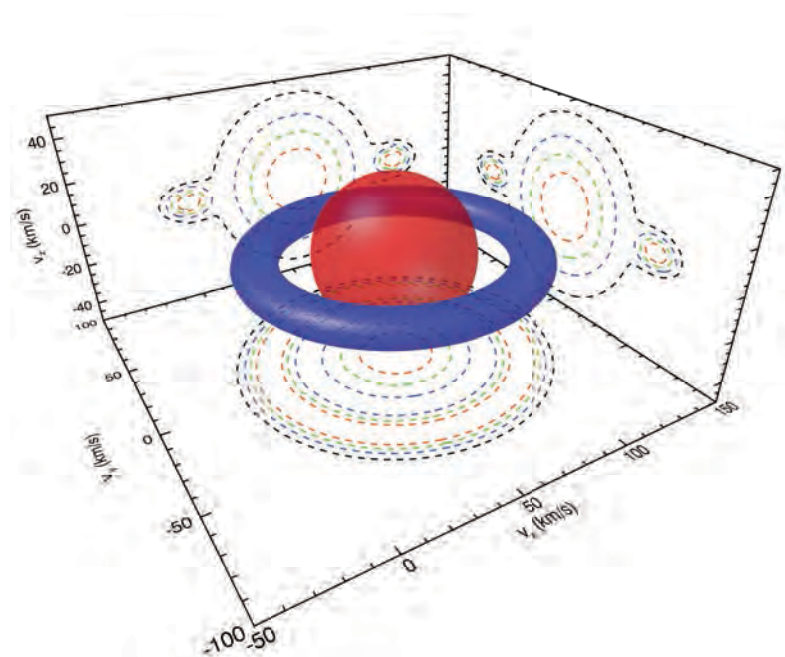
Dory-Guest-Harris (DGH) function

- Ring beams

Anisotropy factor,
N=0 -> Maxwellian

$$f_{DGH}(v_\parallel, v_\perp) = \frac{1}{\pi^{3/2}\Gamma(N+1)a_\parallel a_\perp^2}\left(\frac{v_\perp}{a_\perp}\right)^{2N} e^{-(v_\perp/a_\perp)^2} e^{-(v_\parallel/a_\parallel)^2}$$

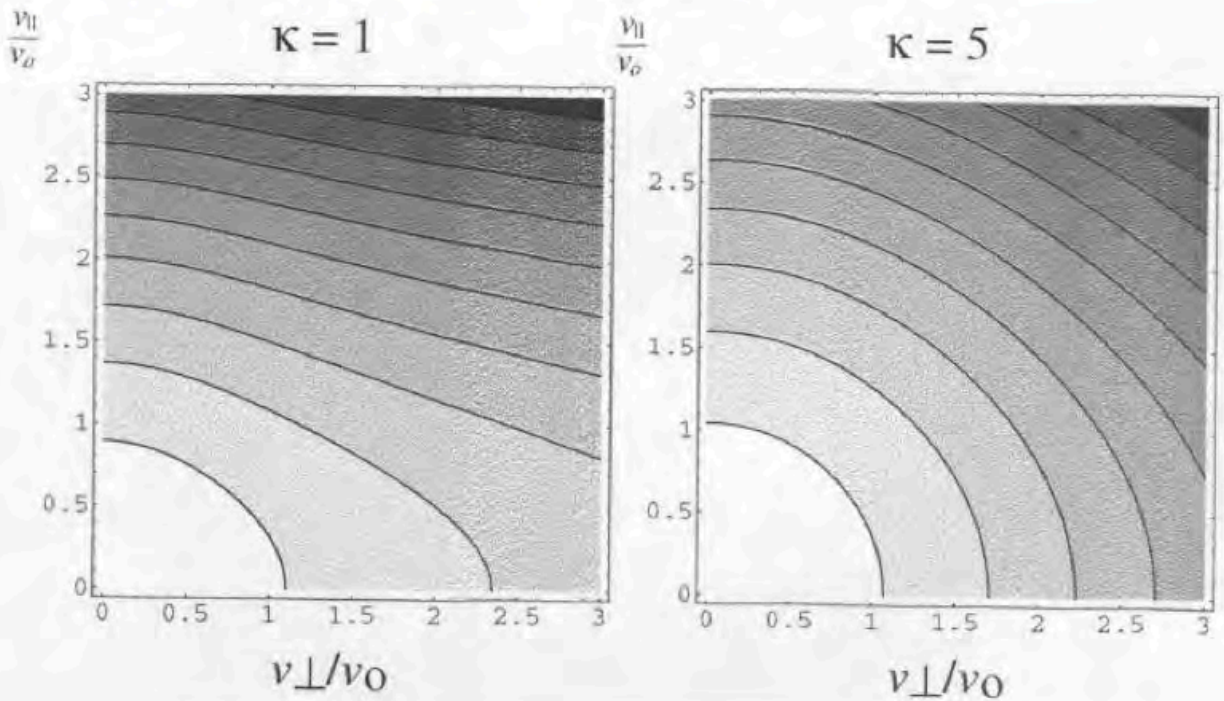
Thermal speed



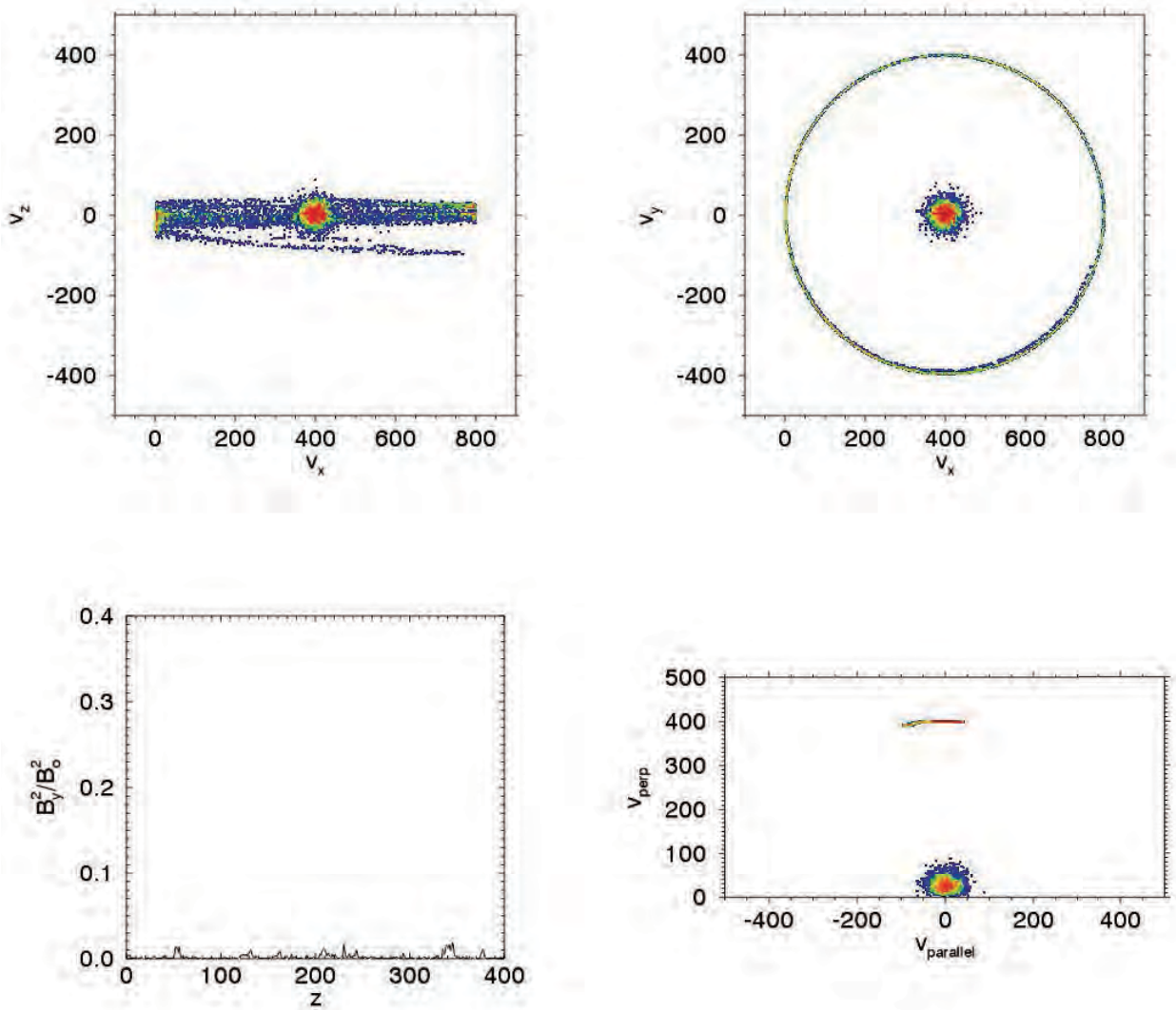
Fried Egg Distribution

Maxwellian parallel to B
Kappa perpendicular to B

Mixed/Evolved pick-up distribution?

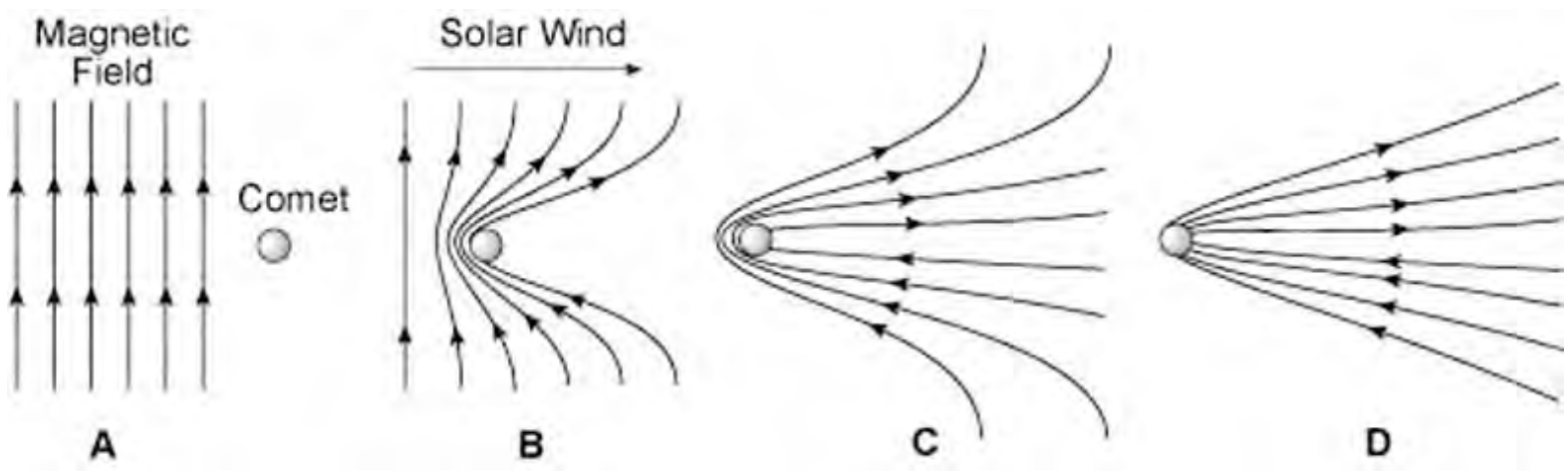


1-D Hybrid simulation interplanetary ion pickup



Solar wind interaction with comets

- Cometary atmosphere (large escaping gas cloud) impedes solar wind.



Maxwell **Stresses**

$$\frac{\partial \rho \mathbf{u}}{\partial t} + \boldsymbol{\nabla} \cdot \left[\rho \mathbf{u}\mathbf{u} + \left(p + \frac{B^2}{2\mu_o} \right) \mathbf{I} - \frac{\mathbf{B}\mathbf{B}}{\mu_o} \right] = 0$$

Force density

$$\mathbf{f} = \boldsymbol{\nabla} \cdot \left(\frac{\mathbf{B}\mathbf{B}}{\mu_o} - \frac{B^2}{2\mu_o} \mathbf{I} \right)$$

$$\mathbf{F} = \int \left[\boldsymbol{\nabla} \cdot \left(\frac{\mathbf{B}\mathbf{B}}{\mu_o} - \frac{B^2}{2\mu_o} \mathbf{I} \right) \right] dV$$

$$\mathbf{F} = \oint_S \left(\frac{\mathbf{B}\mathbf{B}}{\mu_o} - \frac{B^2}{2\mu_o} \mathbf{I} \right) \cdot d\mathbf{a}$$

Maxwell Stress Tensor

- Force per unit area acting on a surface (or stress) acting in the *i*th direction on an element of surface oriented in the *j*th direction.
- Diagonal elements are pressures.
- Off-diagonal are shears

$$\mathbf{F} = \oint_S \left(\frac{\mathbf{BB}}{\mu_o} - \frac{B^2}{2\mu_o}\mathbf{I} \right) \cdot d\mathbf{a}$$

$$T_{ij} = \frac{1}{\mu_o}\left(B_i B_j - \frac{1}{2}\delta_{ij} B^2 \right)$$

Total electromagnetic force on the charges in volume *V*

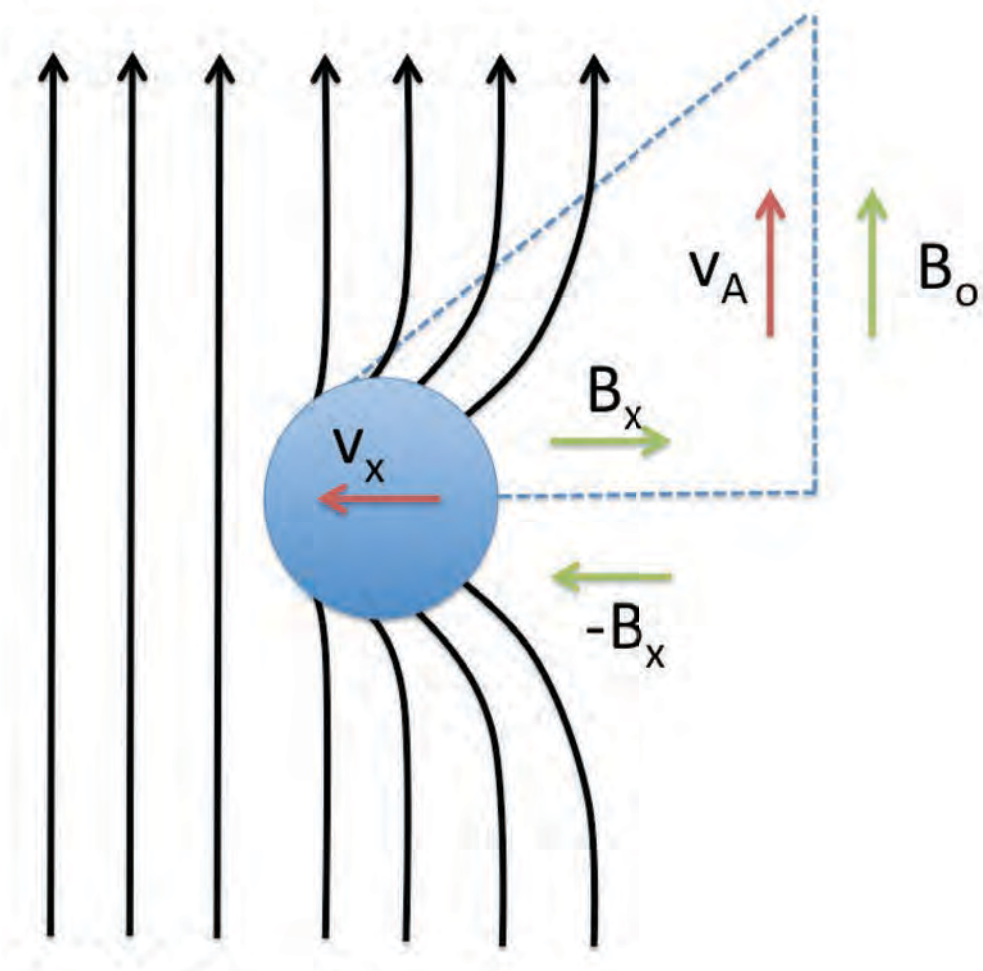
$$\mathbf{F}_{MS} = \oint_S \overleftrightarrow{\mathbf{T}} \cdot d\mathbf{a}$$

Plasma flow/obstacle interaction

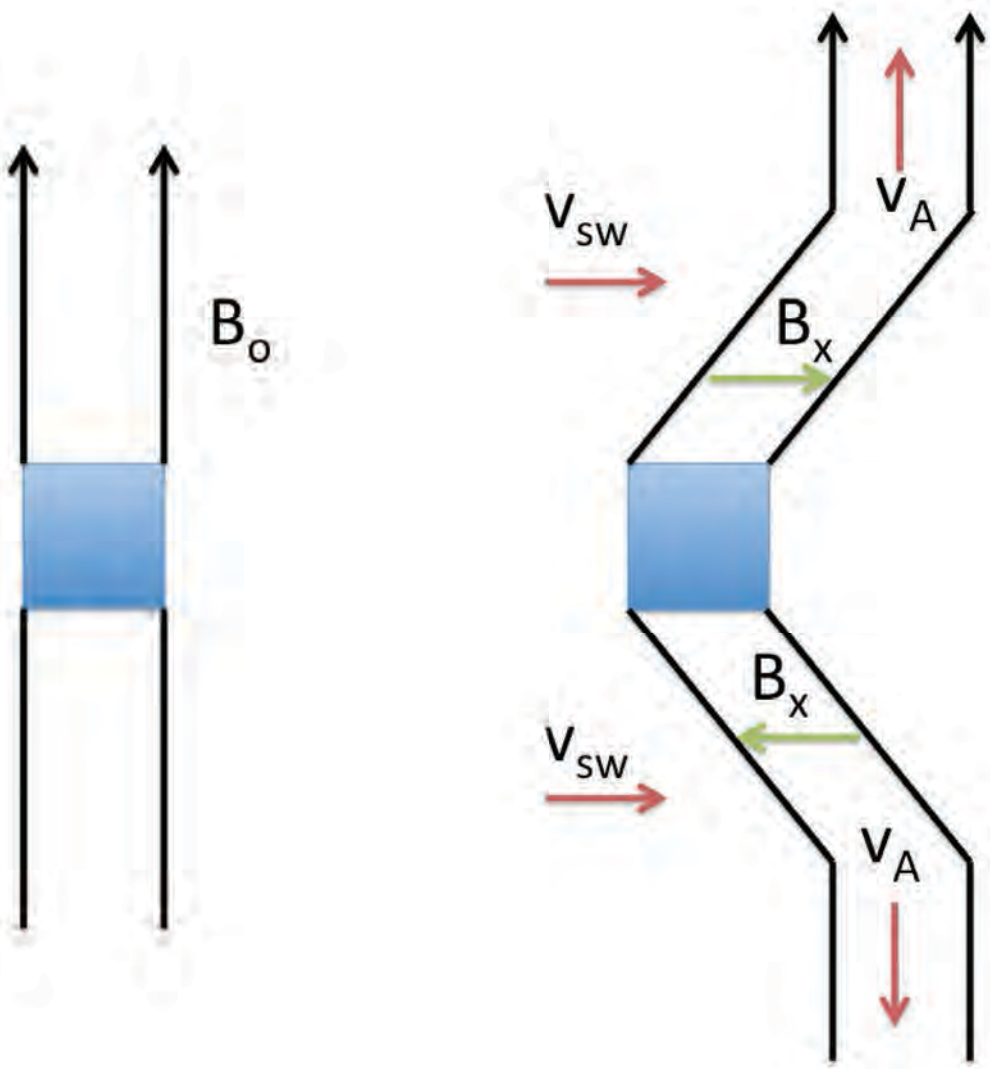
- Any perturbation to flow will perturb the magnetic field (Walen relation)

$$\frac{|\delta v_x|}{v_A} = \frac{|\delta B_x|}{B_o}$$

  - Solar wind IMF
  - Jupiter's magnetic field at Io.



Maxwell Stress Tensor: Example



Maxwell Stress Tensor: Example

- On the top surface

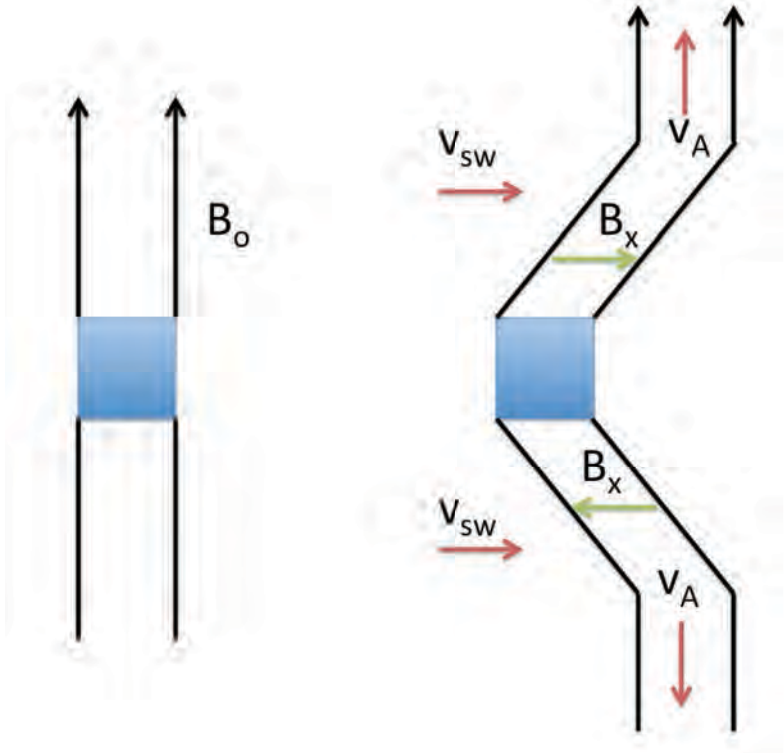
$$\mathbf{B} = B_x\hat{\mathbf{x}} + B_o\hat{\mathbf{z}}$$

- On the bottom surface

$$\mathbf{B} = -B_x\hat{\mathbf{x}} + B_o\hat{\mathbf{z}}$$

- On the other sides

$$\mathbf{B} = B_o\hat{\mathbf{z}}$$



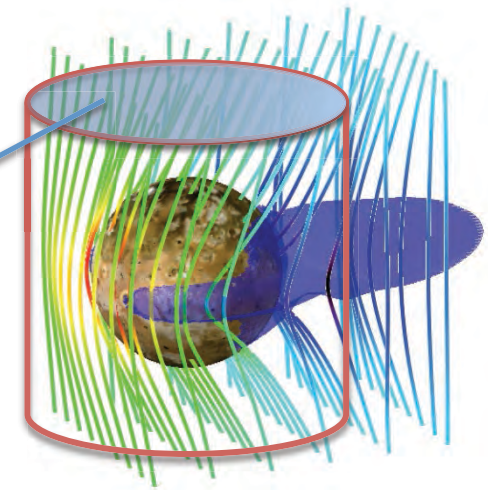
Maxwell Stress Tensor: Example

$$
\begin{aligned}
\mathbf{F} &= \oint_S \overleftrightarrow{\mathbf{T}} \cdot d\mathbf{a} \\
&= \left[(T_{xz} da)_{top} + (T_{xz} da)_{bottom} \right] \hat{\mathbf{x}} \\
&= \left[\frac{+B_x B_o}{\mu_o} (+L^2) + \frac{-B_x B_o}{\mu_o} (-L^2) \right] \hat{\mathbf{x}} \\
&= \frac{2 B_x B_o}{\mu_o} L^2 \hat{\mathbf{x}}
\end{aligned}
$$

Strong interaction and saturation

- Maxwell stress

$$\frac{dp_x}{dt} = \frac{2(\delta B_x)B_z A}{\mu_o} = (2\rho_{sw} v_A A) v_x$$



- Plasma mass coupling rate to solar wind

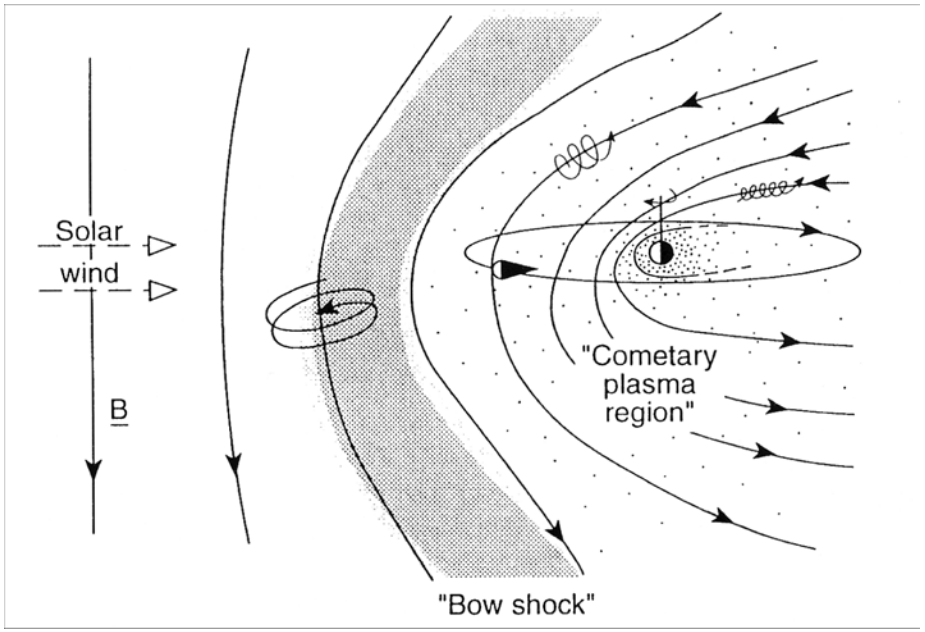
$$\dot{M}_{sw} = 2\rho_{sw} v_A A$$

$$\dot{M}_{sw} < \dot{M}_{comet}$$

Long plasma tail

Question(s)?

- Is it possible to progressively slow the solar wind to subsonic speeds and avoid a shock?
- If not, where will the shock form?



Estimating cometary bow shock location

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SOLAR WIND STAGNATION NEAR COMETS

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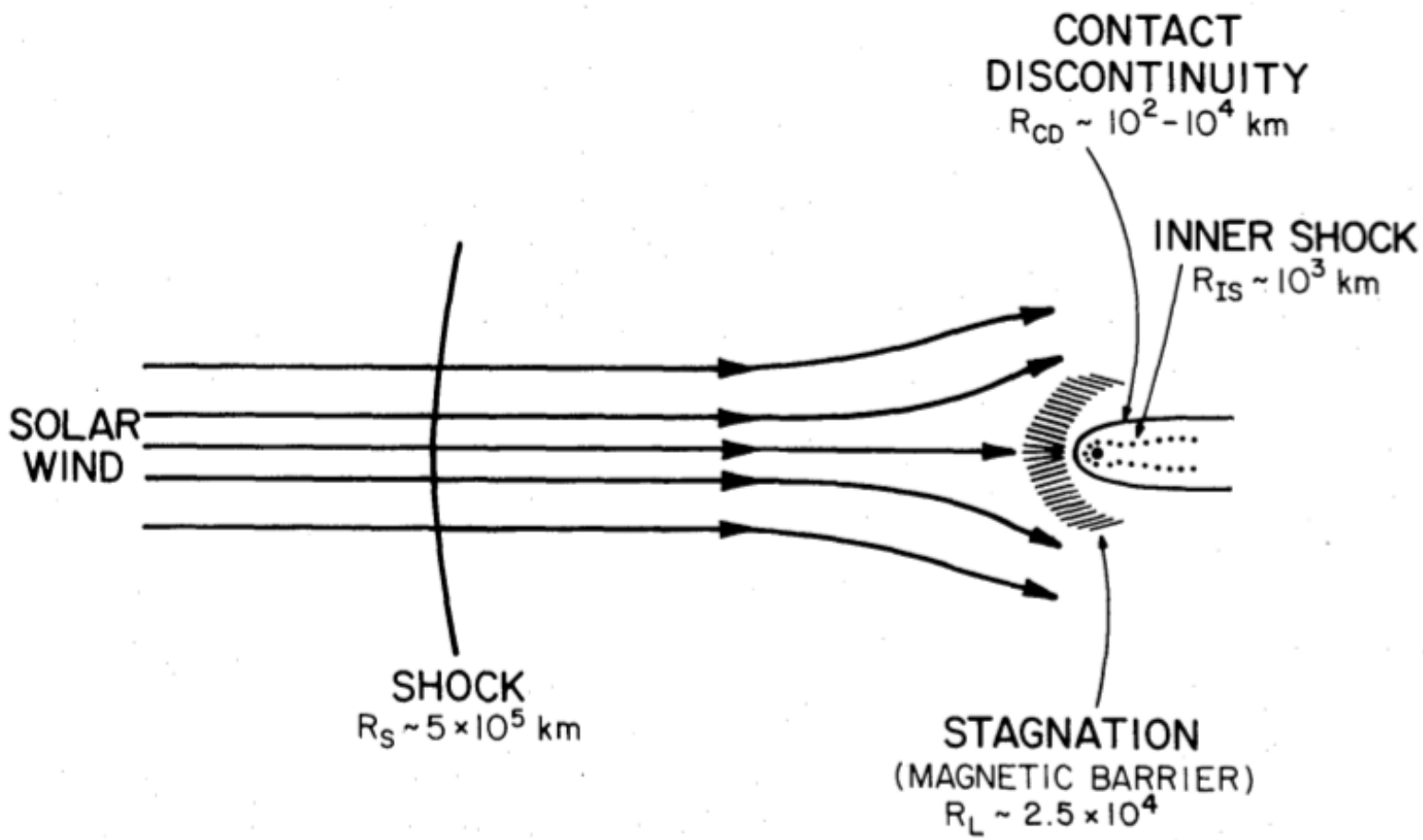
ABSTRACT

The nature of the solar wind flow near comets is examined analytically in this paper. In particular, typical values for the stagnation pressure and magnetic barrier strength are estimated, taking into account magnetic field line tension and change-exchange cooling of the mass-loaded solar wind. A knowledge of the strength of the magnetic barrier is required in order to determine the location of the ionopause surface which separates the contaminated solar wind plasma from the outflowing plasma of the cometary ionosphere.

Subject headings: comets — Sun: solar wind

Basic features of cometary environment

GALEEV, CRAVENS, AND GOMBOSI



Equations for unshocked solar wind flow

$$\frac{d}{dx}[\rho_i u f(\mu, u)] = \frac{Q_o m_i}{4\pi u_{esc} \tau r^2} \delta\left(\mu - \frac{mu^2}{2B}\right)$$

Cometary ions

Contaminated solar wind

Ring/Shell distribution

$$\frac{d(\rho u)}{dx} = \frac{Q_o m_i}{4\pi u_{esc} \tau r^2}$$

$$\frac{d}{dx}\left(\rho u^2 + p_\perp + \frac{B^2}{2\mu_o}\right) = 0$$

Unshocked solar wind flow

$$\rho_i u f(u,\mu) = \int_{u_\infty}^{u} \frac{d(\rho' u')}{du'} \delta\left(\mu - \frac{m_i u'^2}{2B'}\right) du'$$

Unperturbed solar wind

$$p_\perp \approx p_{\perp i} = \int_{m_i u^2/2B}^{m_i u_\infty^2/2B_\infty} \rho_i f(u,\mu) \left(\frac{\mu B}{m_i}\right) d\mu$$

Assume that pressure is due entirely to pickup ions
(neglect magnetic field and solar wind protons)

Unshocked solar wind flow

$$\rho u = \rho_\infty u_\infty \left(\frac{4u_\infty}{3u} - \frac{u_\infty^2}{3u^2} \right)$$

$$\hat{\rho}\hat{u} = 1 + \frac{Q_o m_i}{4\pi u_{esc} \tau \rho_\infty u_\infty} \frac{1}{r}$$

Normalized to upstream conditions

Shock stand-off distance

$$R_s = \frac{Q_o m_i}{4\pi u_{esc} \tau \rho_\infty u_\infty [(\hat{\rho}\hat{u})_c - 1]}$$

- Continuous solar wind flow only possible until the mean molecular mass of contaminated solar wind reaches of critical value

$$(\hat{\rho}\hat{u})_c \approx \frac{4}{3}$$

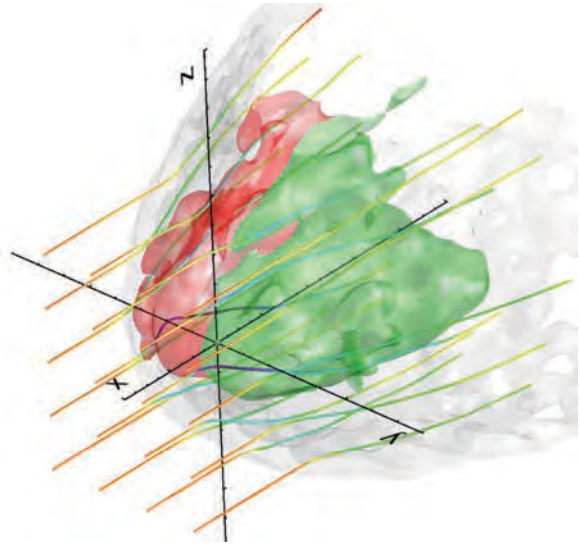
Shock stand-off distance

- Numerical simulations show that the shock is weak, i.e. M=2

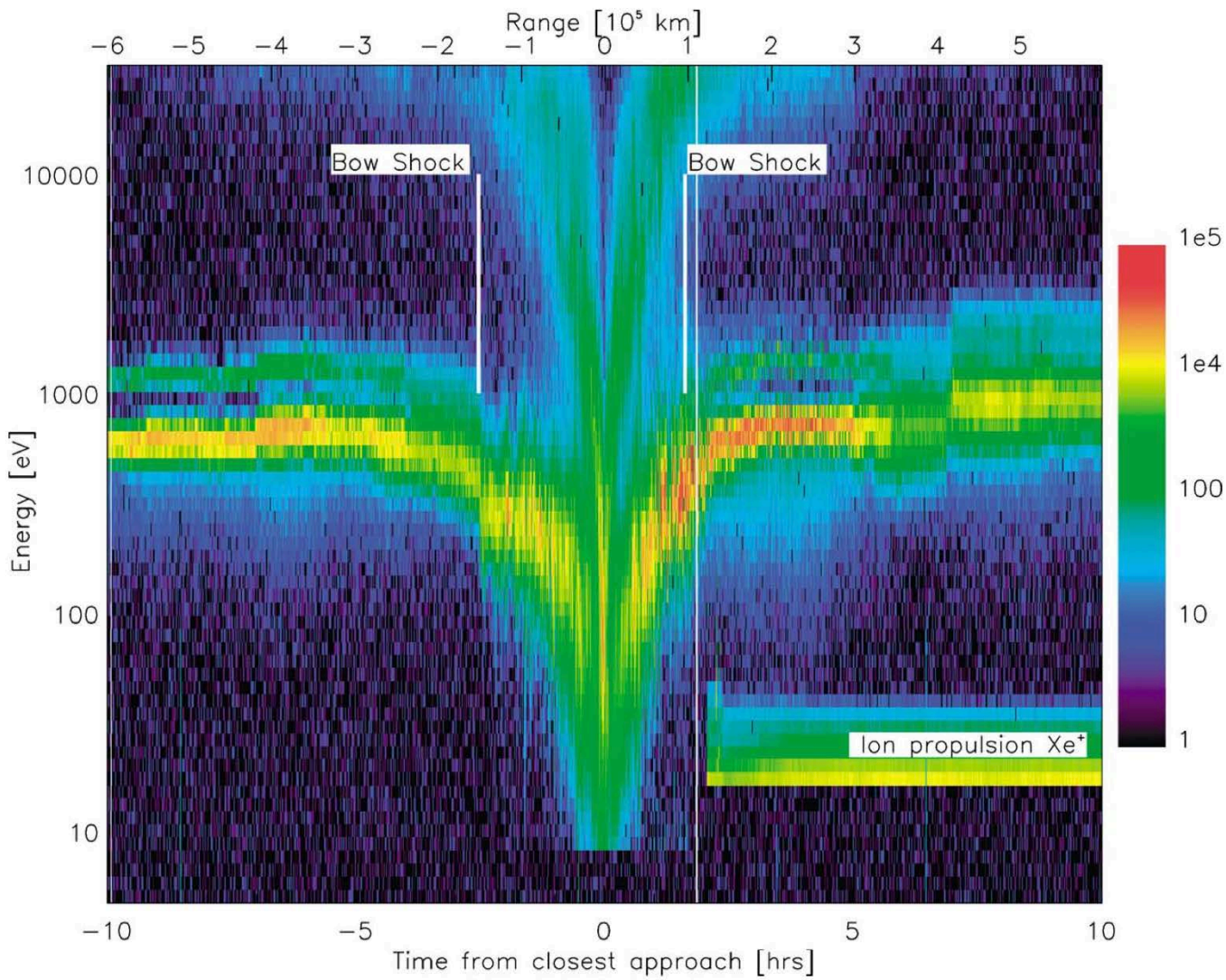
The following choice of parameters is appropriate for a Halley-type comet at 1 AU: $n_\infty = 6\ \mathrm{cm}^{-3}$, $v_\infty = 400\ \mathrm{km\ s}^{-1}$, $m_i/m_p = 18$, $V_g = 1\ \mathrm{km\ s}^{-1}$, $\tau = 10^6$ s, and $Q_n = 2.5 \times 10^{29}\ \mathrm{s}^{-1}$. The distance to the shock given by equation (9) is 8×10^5 km from the nucleus along the Sun-comet line.

Plasma interaction as an atmospheric diagnostic

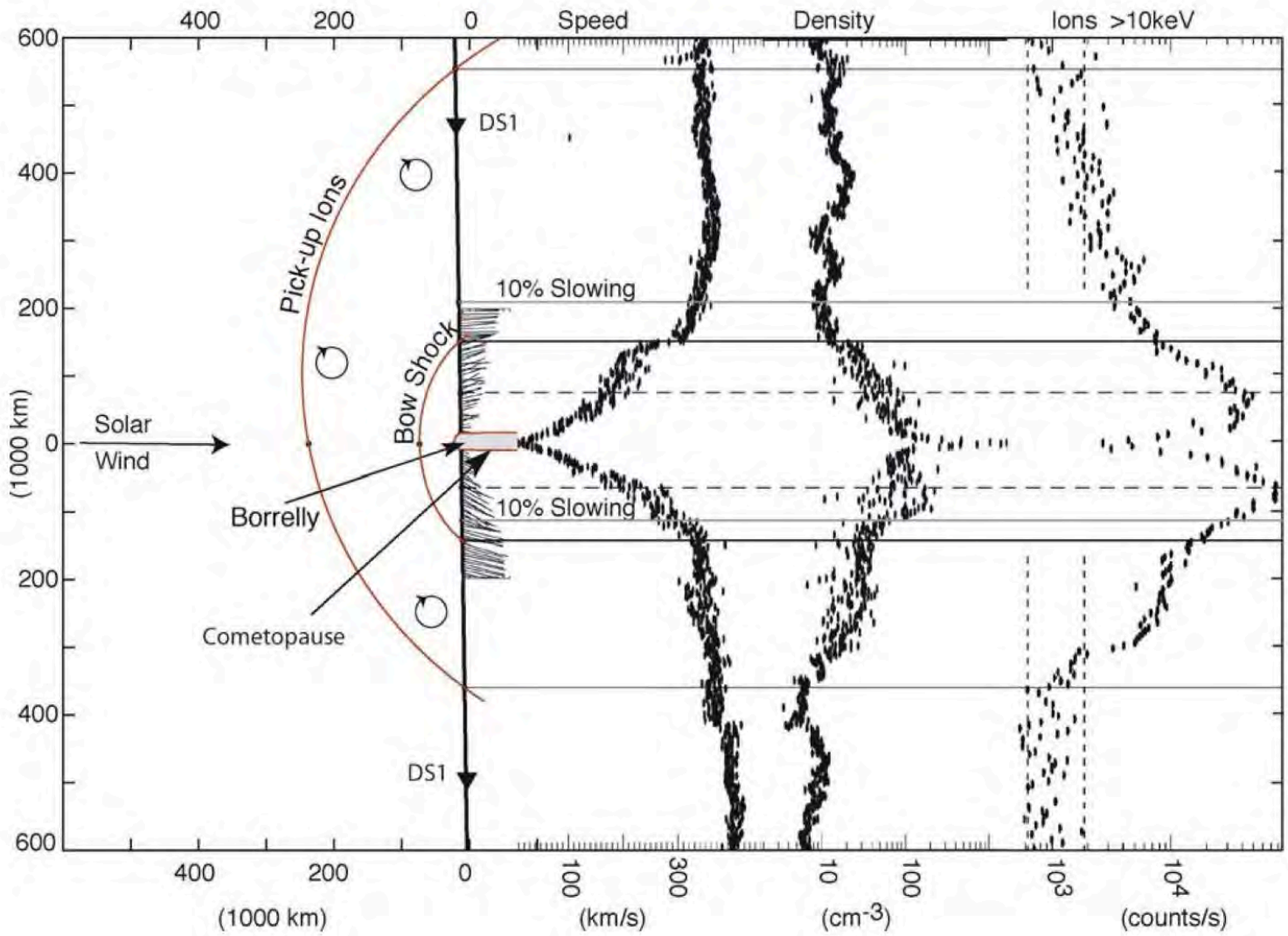
- Tenuous neutral gases are not easily measured
- But the ionized products are detectable at very low concentrations with in situ plasma detectors



Solar wind interaction with Comet 19P/Borrelly



Borrelly's plasma environment



Hybrid code

- Kinetic treatment of ions
- Fluid treatment of electrons (massless)
- Electron momentum equation

$$\mathbf{E} = -\mathbf{u}_e \times \mathbf{B}$$

- Ampere's Law

$$\mathbf{u}_e = \mathbf{u}_i - \frac{\nabla \times \mathbf{B}_1}{\alpha n}$$

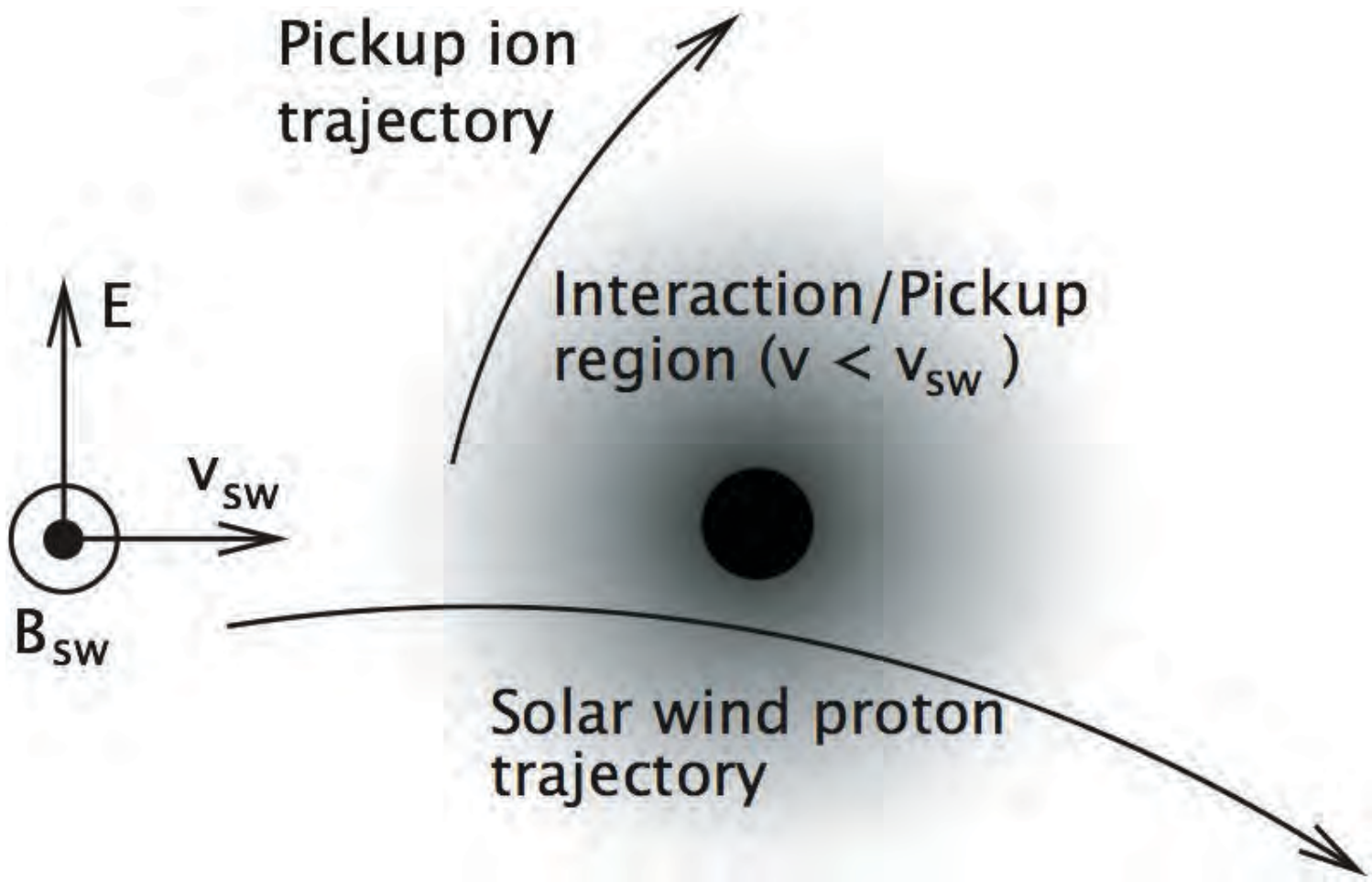
- Ion momentum equation

$$\frac{d\mathbf{v}}{dt} = \mathbf{E} + \mathbf{v} \times \mathbf{B}$$

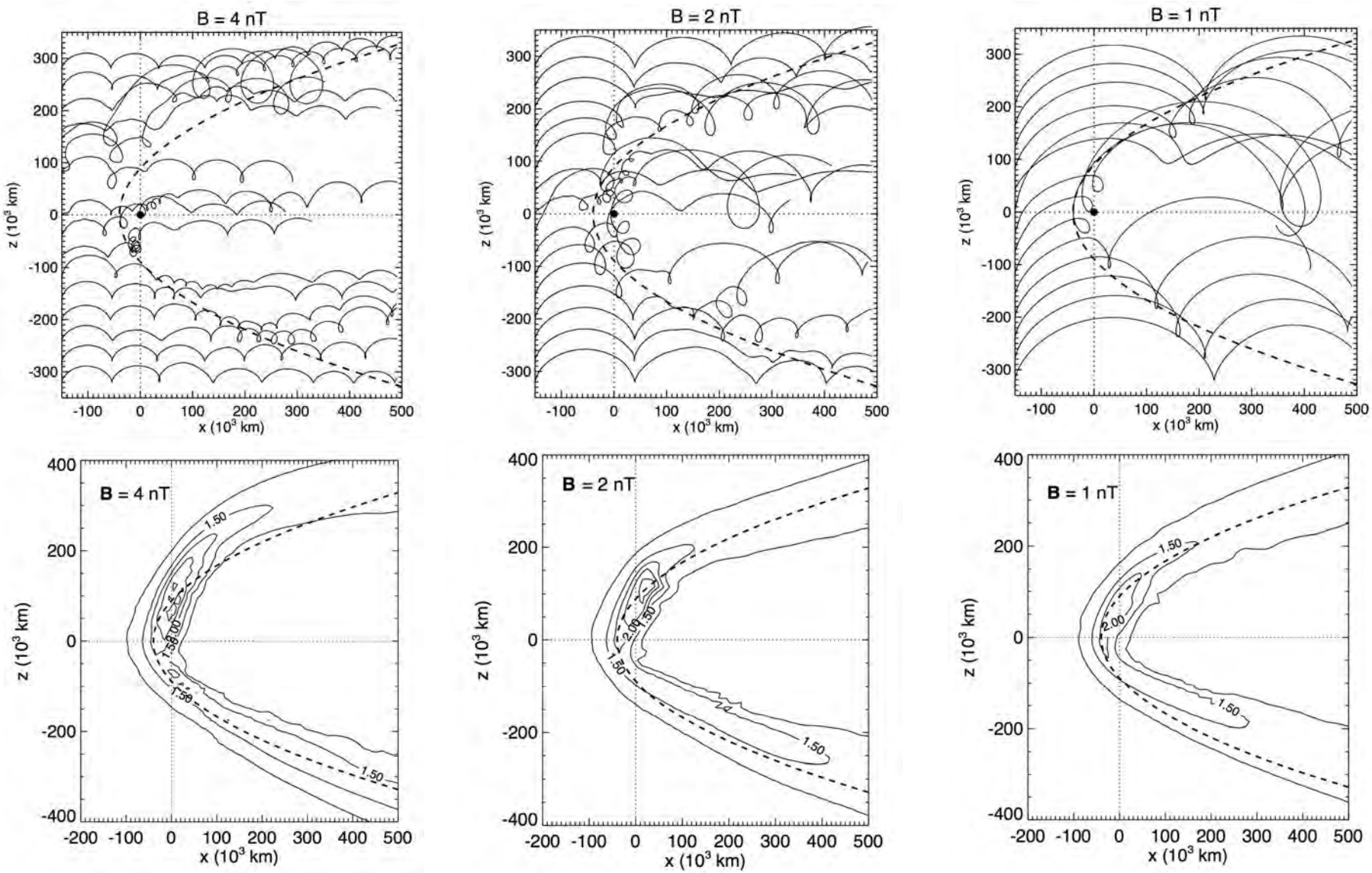
- Faraday's Law

$$\frac{\partial \mathbf{B}_1}{\partial t} = -\nabla \times \mathbf{E}$$

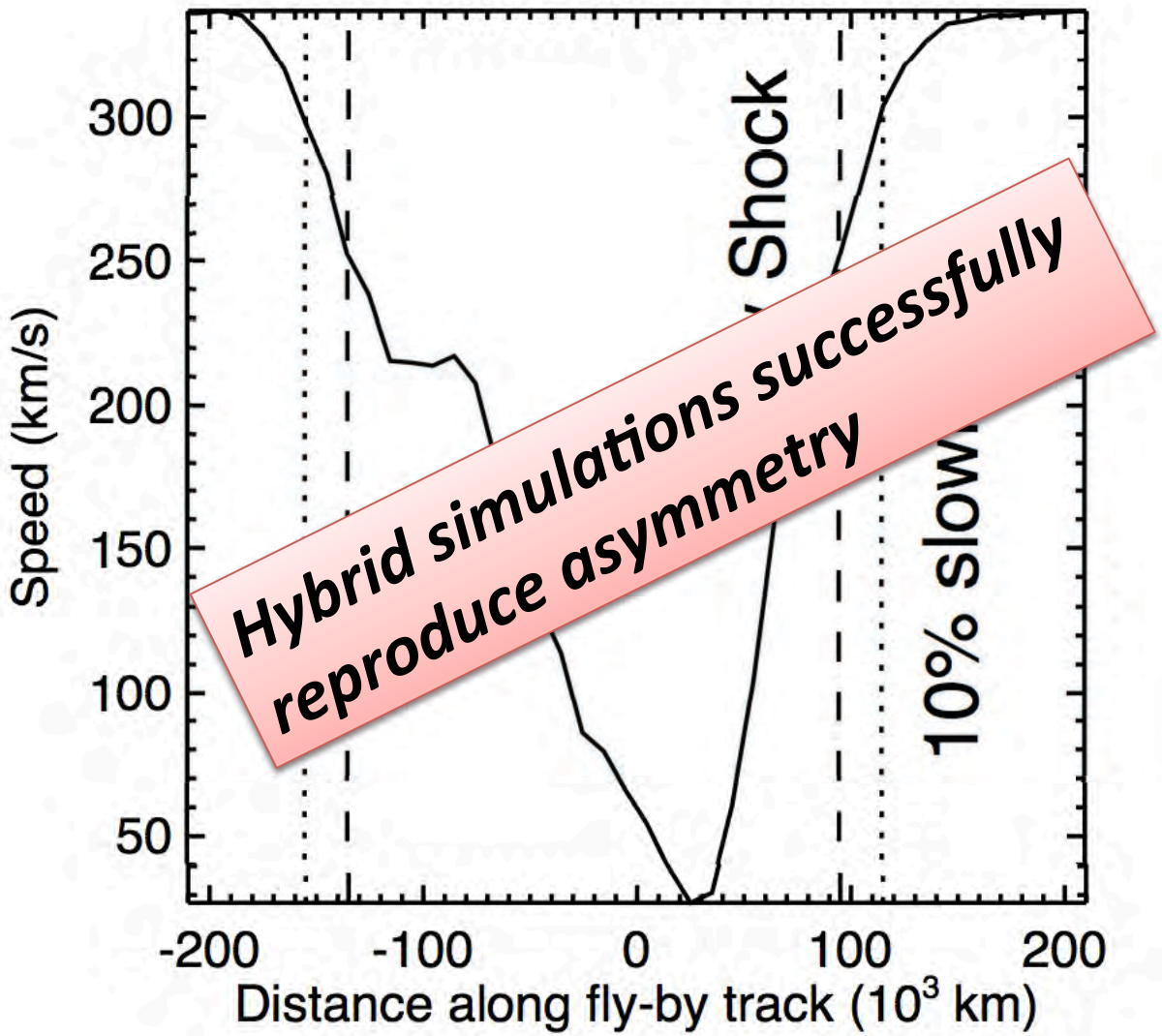
Simulation geometry



Gyroradius effects at Borrelly



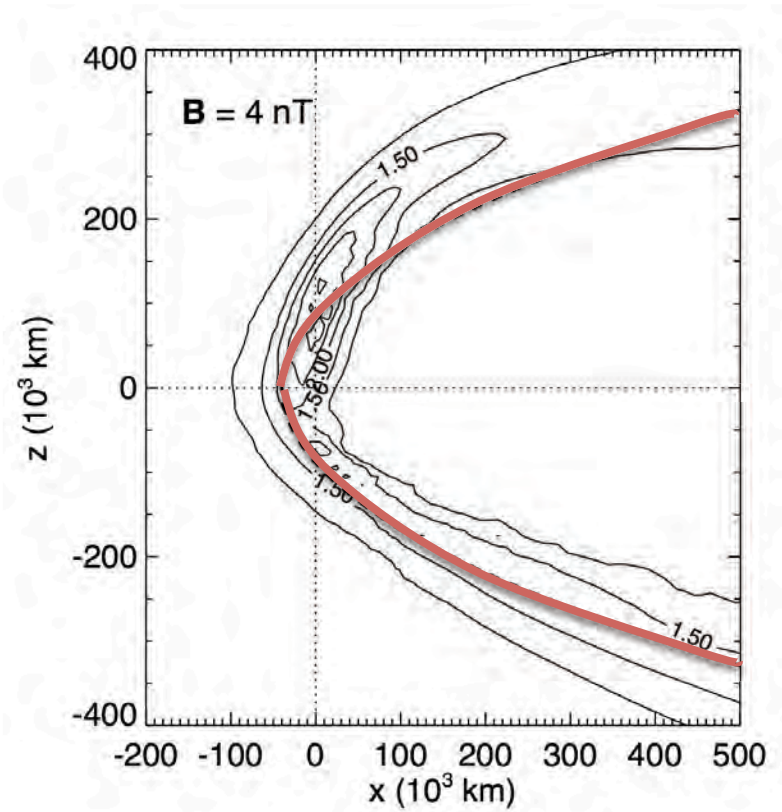
Borrelly Hybrid Simulation

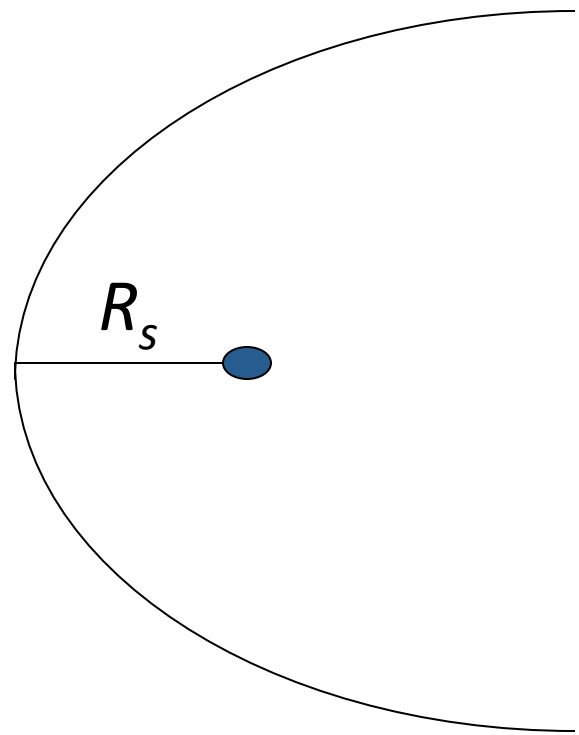


Solar wind stagnation near comets

[*Biermann et al.*, 1967; *Galeev et al.*, 1985]

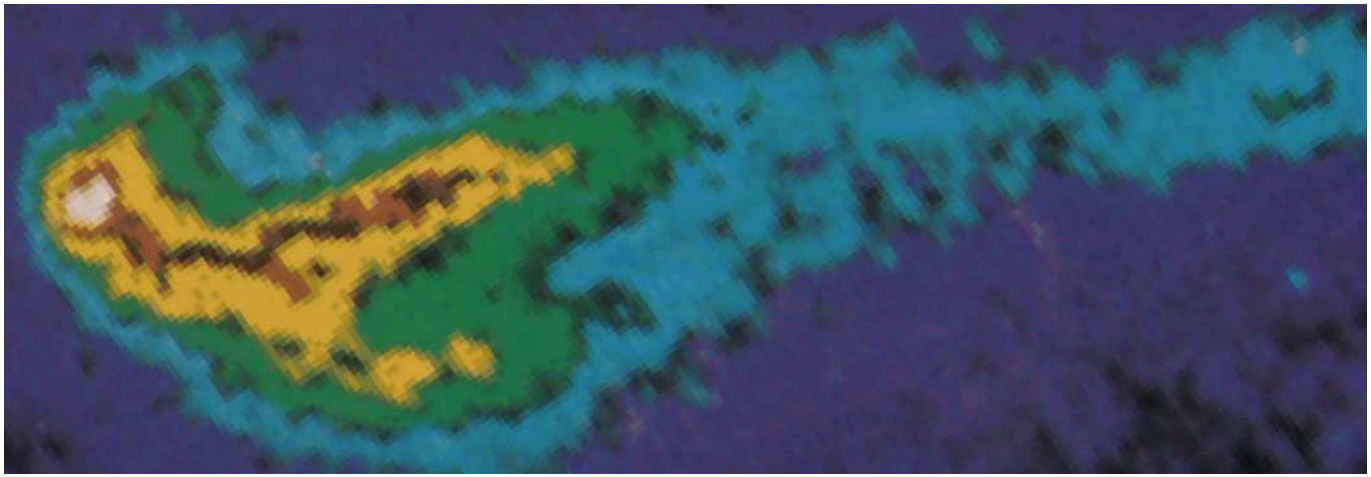
$$R_s = \frac{Q_n m_i}{4\pi v_{esc} \tau \rho_\infty u_\infty [\hat{\rho}\hat{u} - 1]}$$





AMPTE artificial comet

- AMPTE artificial comet
  - On December 27, 1984, a cloud of neutral barium vapor was released into the solar wind outside of the bow shock by the Active Magnetospheric Particle Trace Experiment (AMPTE) satellite.

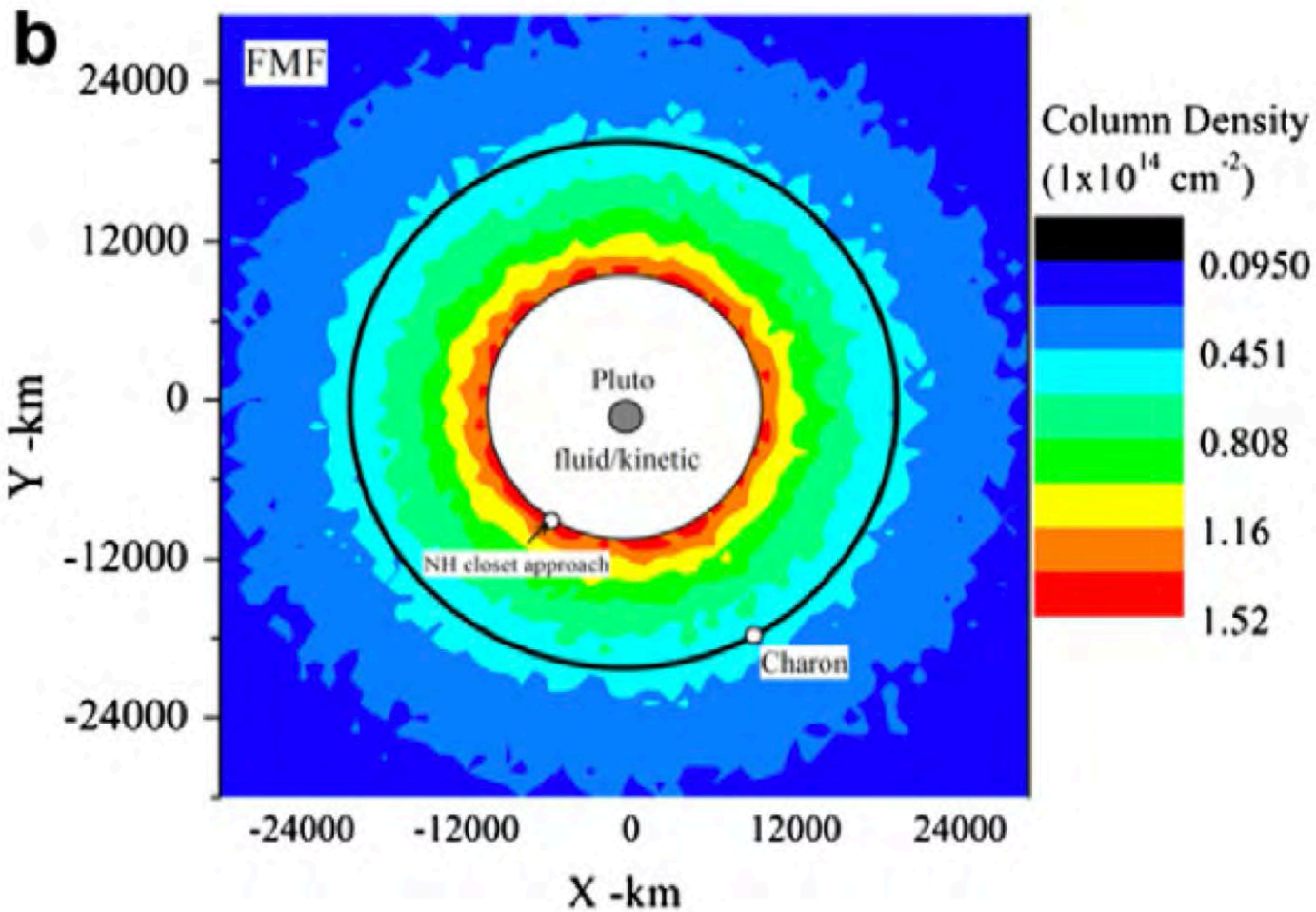


Pluto's Escaping Atmosphere

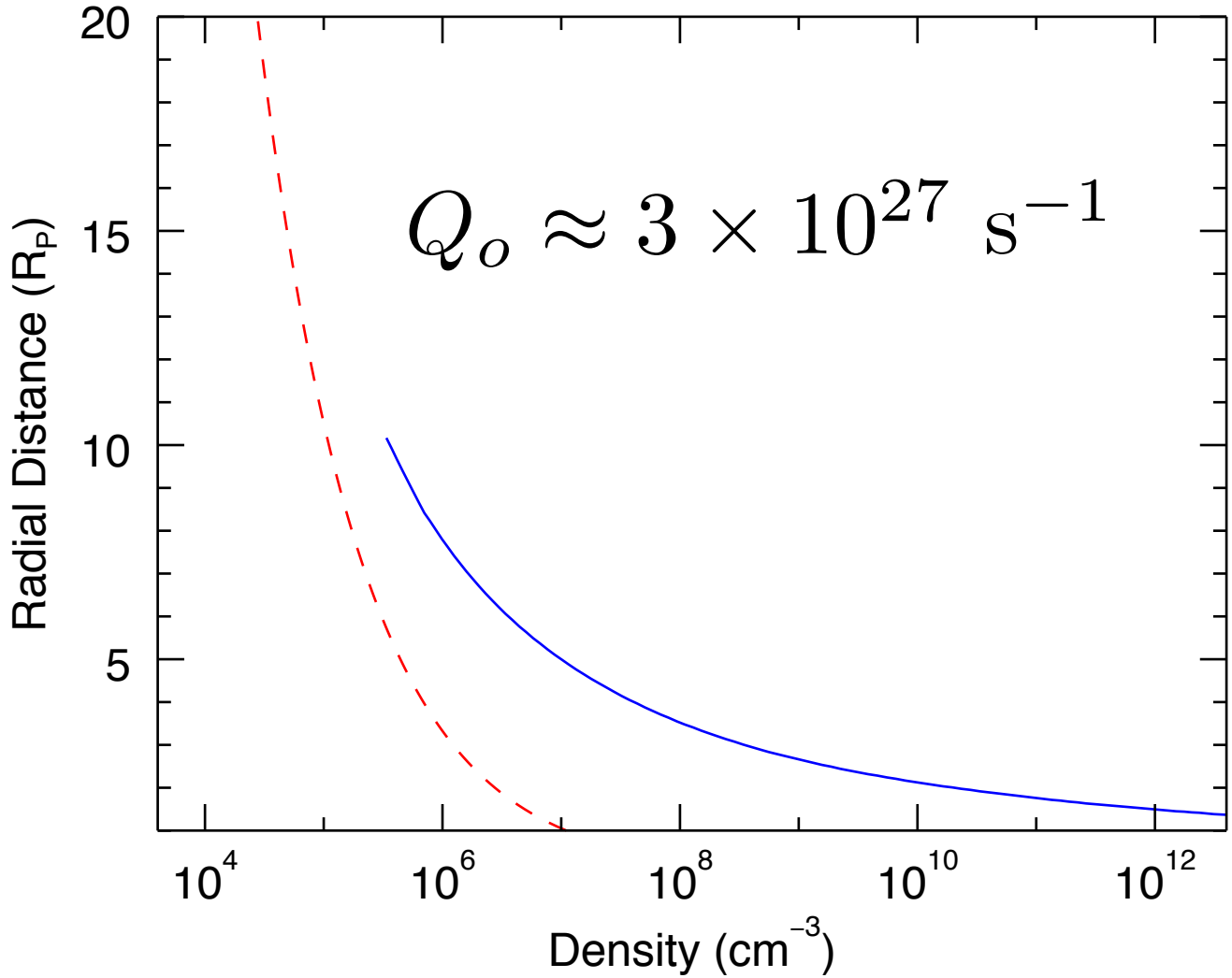
- Hydrodynamic escape/Enhanced Jeans escape
- Atmospheric escape, Q_o

McNutt (1989)	CH_4	Q_o=2.3-4.4x10^{27} s^{-1}
Krasnopolsky [1999]	N_2	Q_o~2.0x10^{27} s^{-1}
Strobel [2007]	N_2	Q_o~2.0x10^{27} s^{-1}
Tian and Toon [2005]	N_2	Q_o~2.0x10^{28} s^{-1}

Pluto's extended atmosphere
[*Tucker et al.*, 2012]

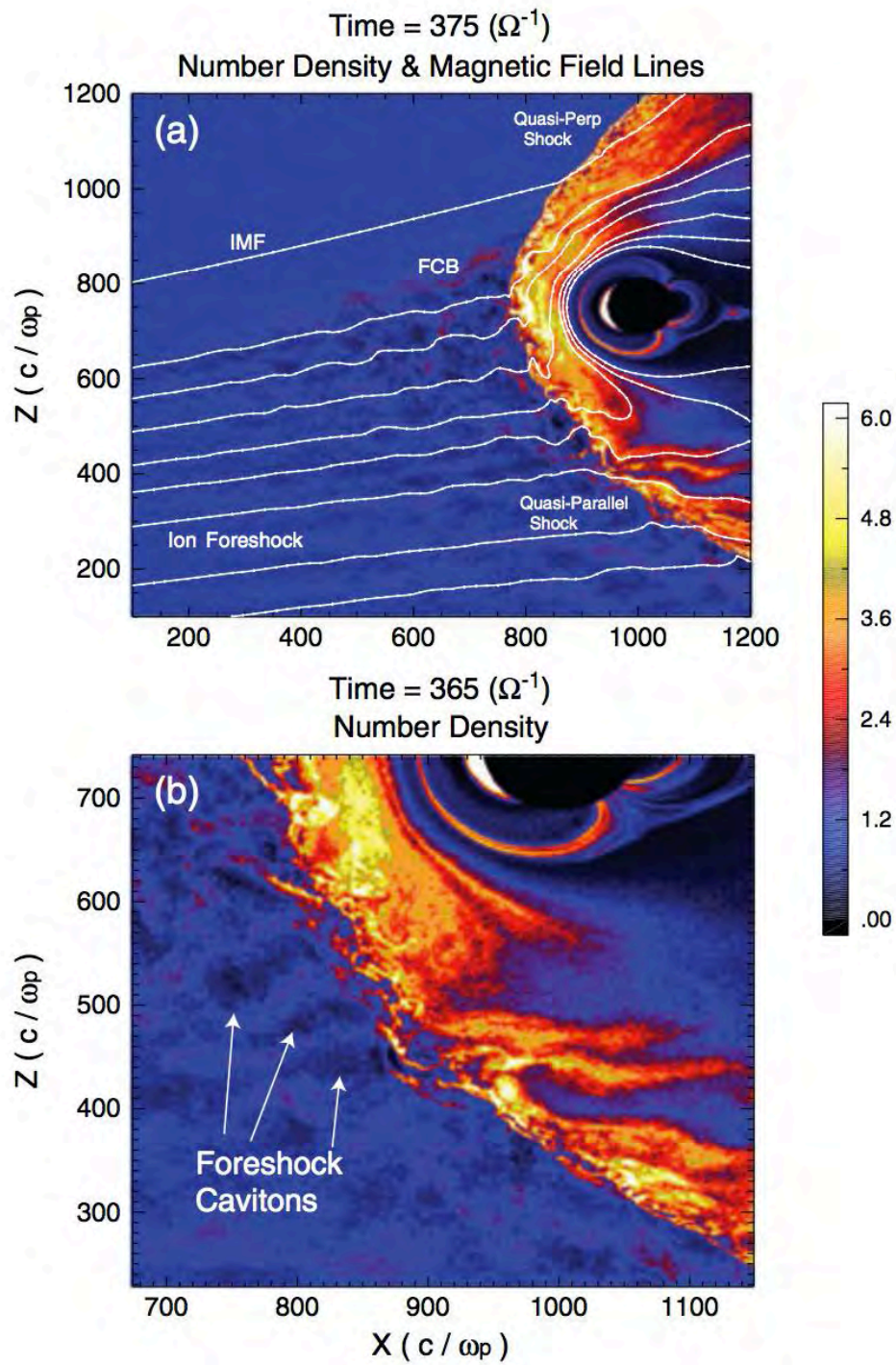


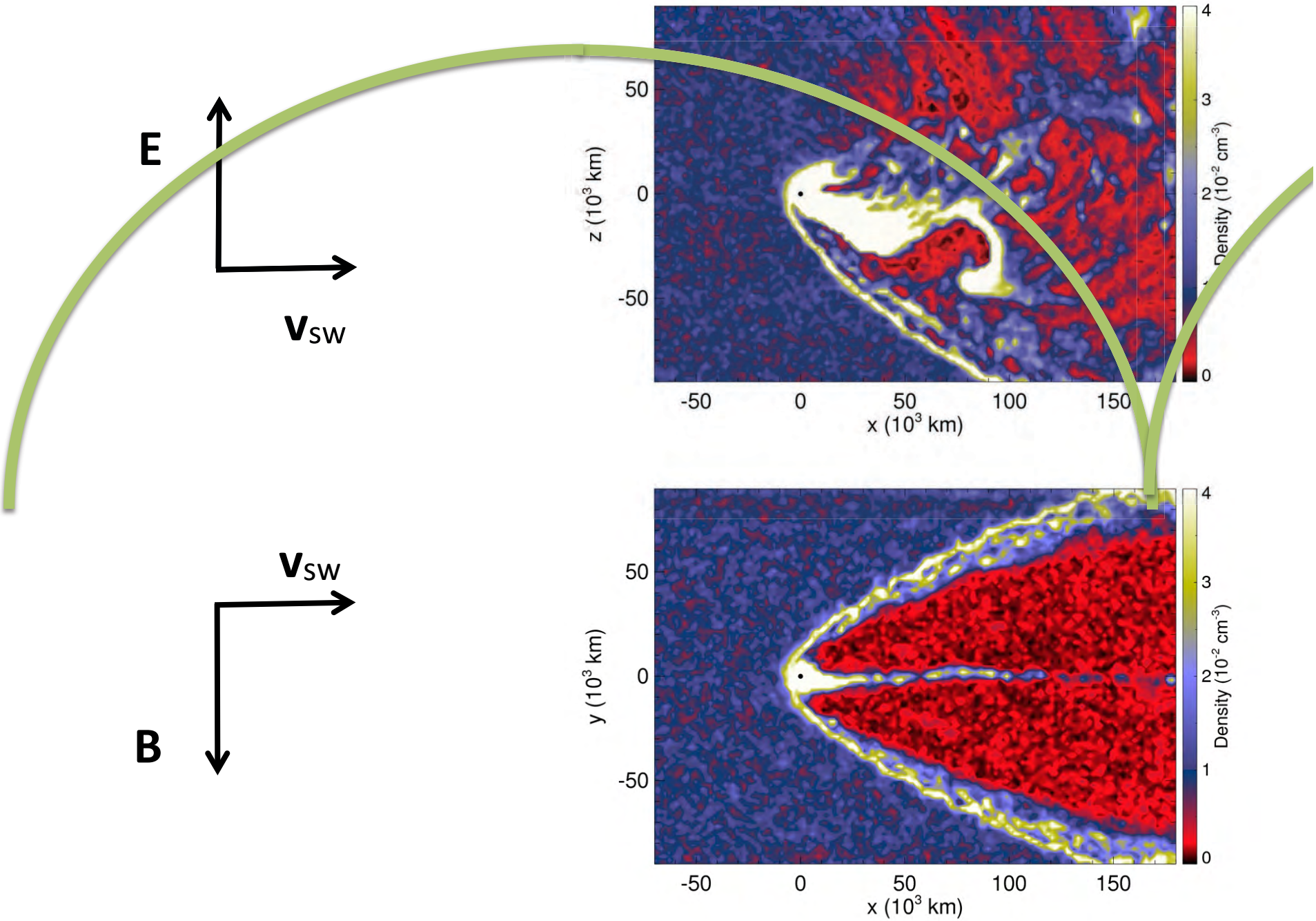
Strobel Atmosphere



Hybrid simulations of Earth's BS [*Omidi et al*., 2013]

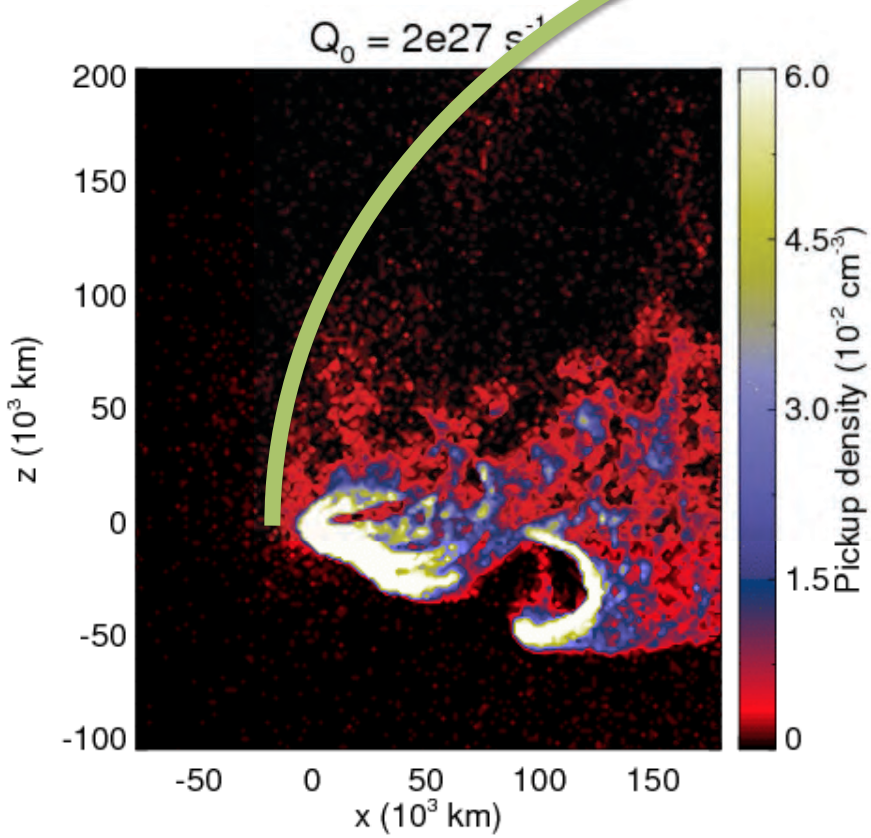
- Hot flow anomalies [*Zhang et al*., 2012]
- Density fluctuations in the solar wind-> changes local jump condition.

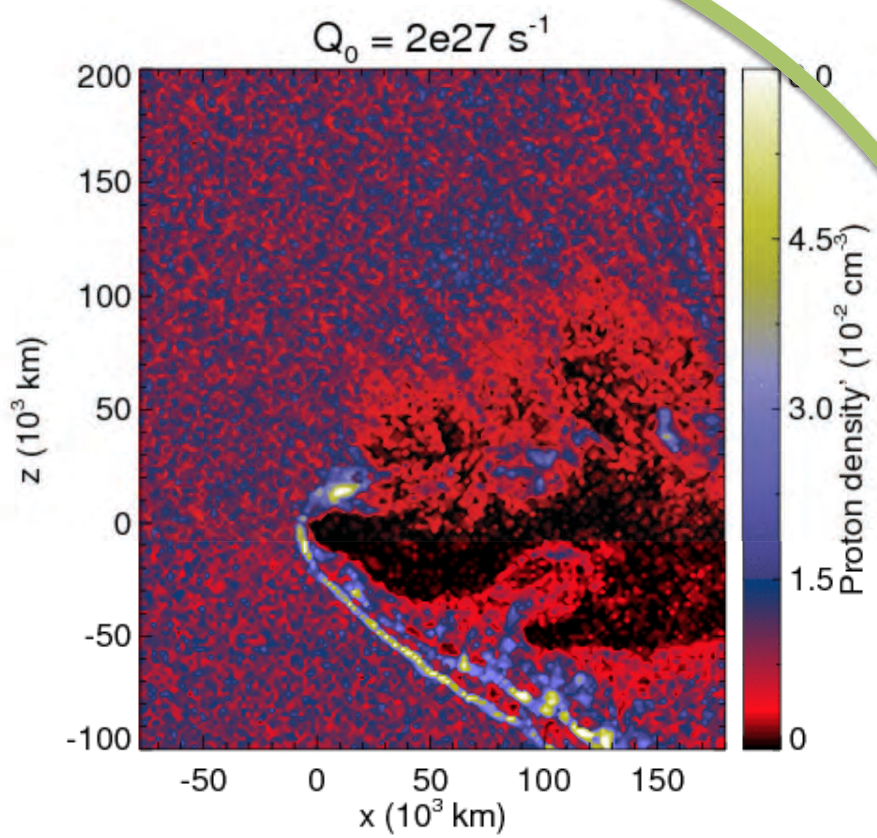



E
v_{SW}
v_{SW}
B
z (10^3 km)
x (10^3 km)
Density (10^{-2} cm^{-3})
y (10^3 km)
x (10^3 km)
Density (10^{-2} cm^{-3})

Baseline Case

(B_{IMF} = 0.2 nT, Q_o = 2x10^{27} s^{-1})

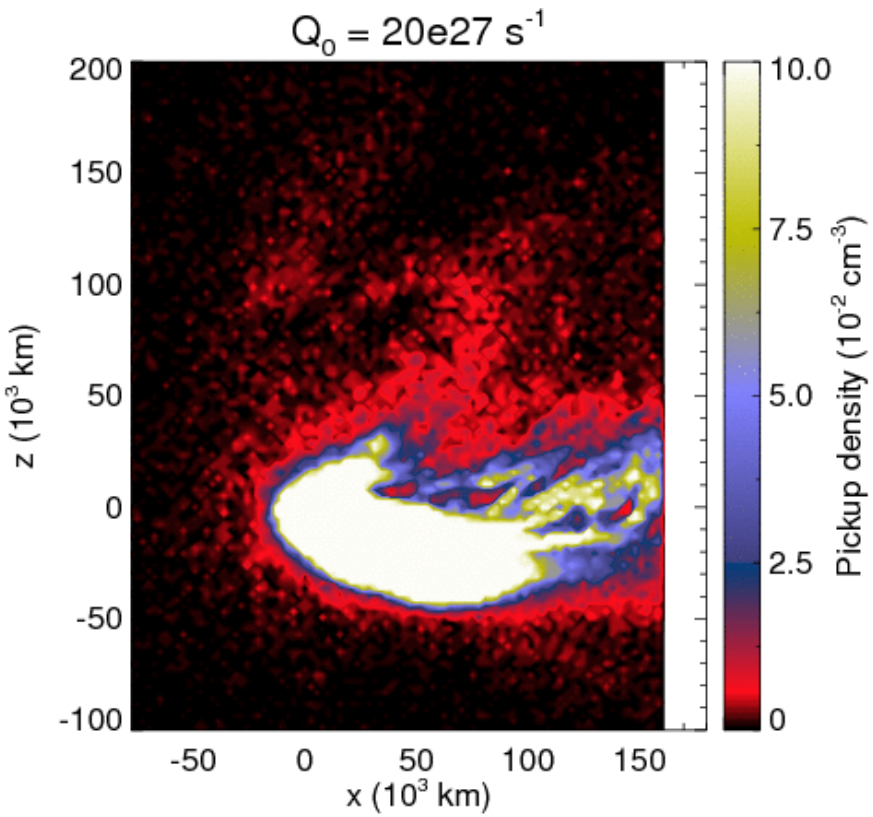




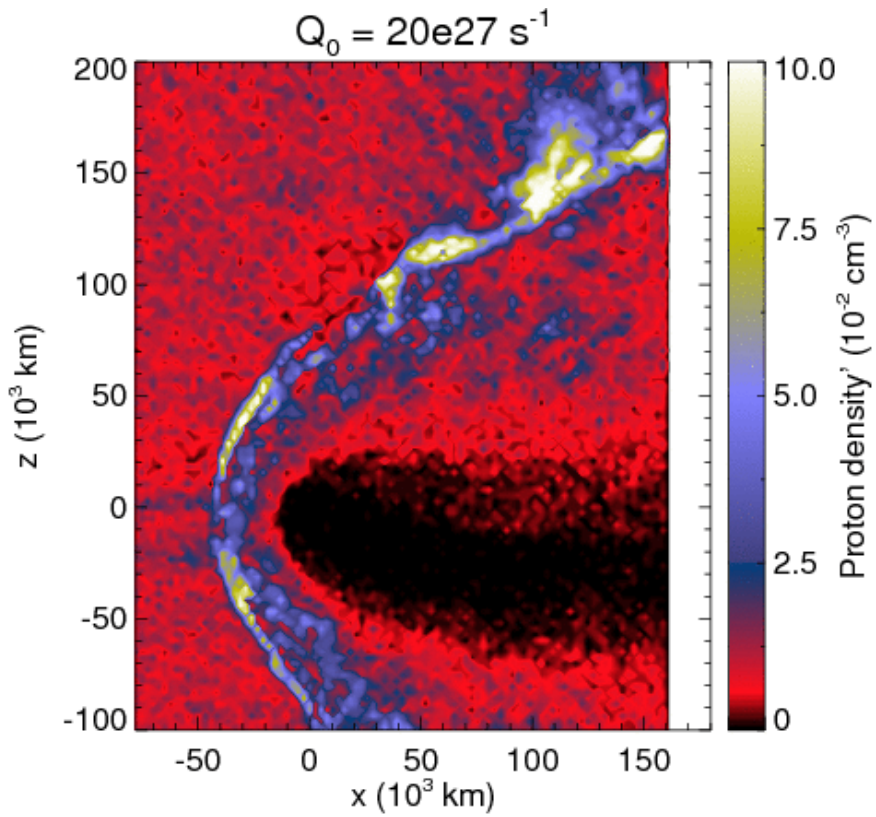
Pickup Ions

Solar Wind Protons

High Q_o
(B_{IMF} = 0.2 nT, Q_o = 20x10^{27} s^{-1})

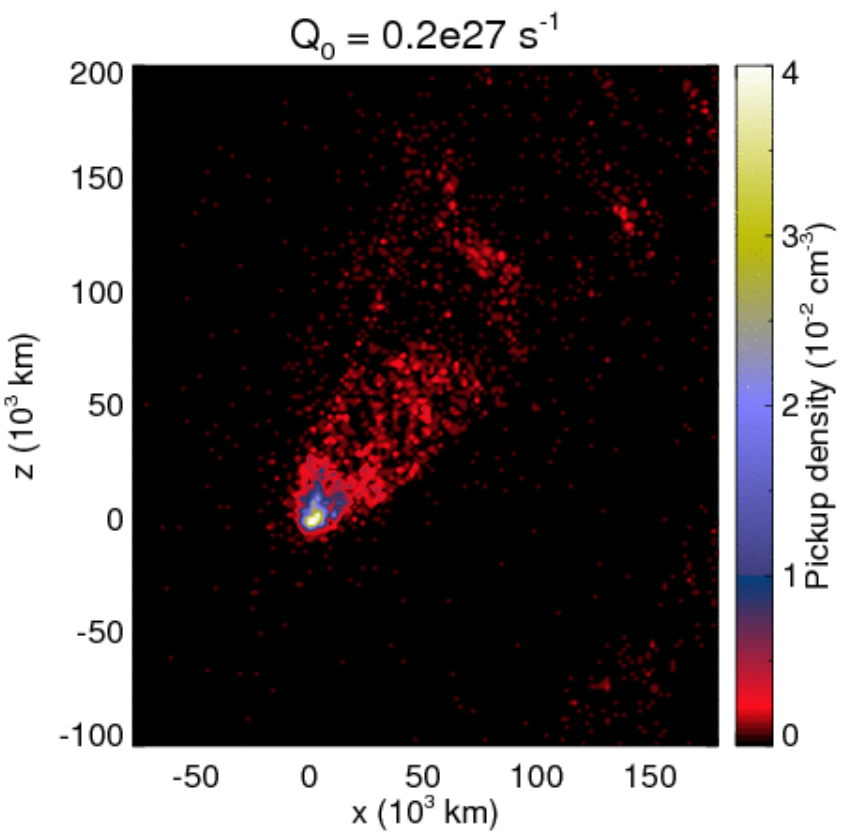


Pickup Ions

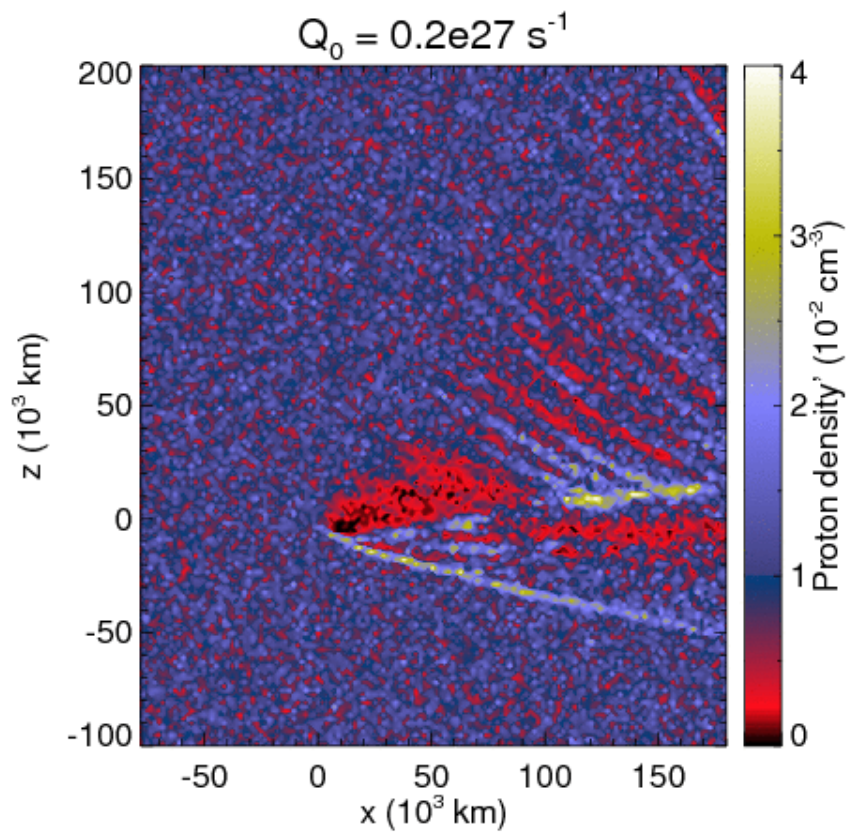


Solar Wind Protons

Low Q_o
(B_{IMF} = 0.2 nT, Q_o = 0.2x10^{27} s^{-1})

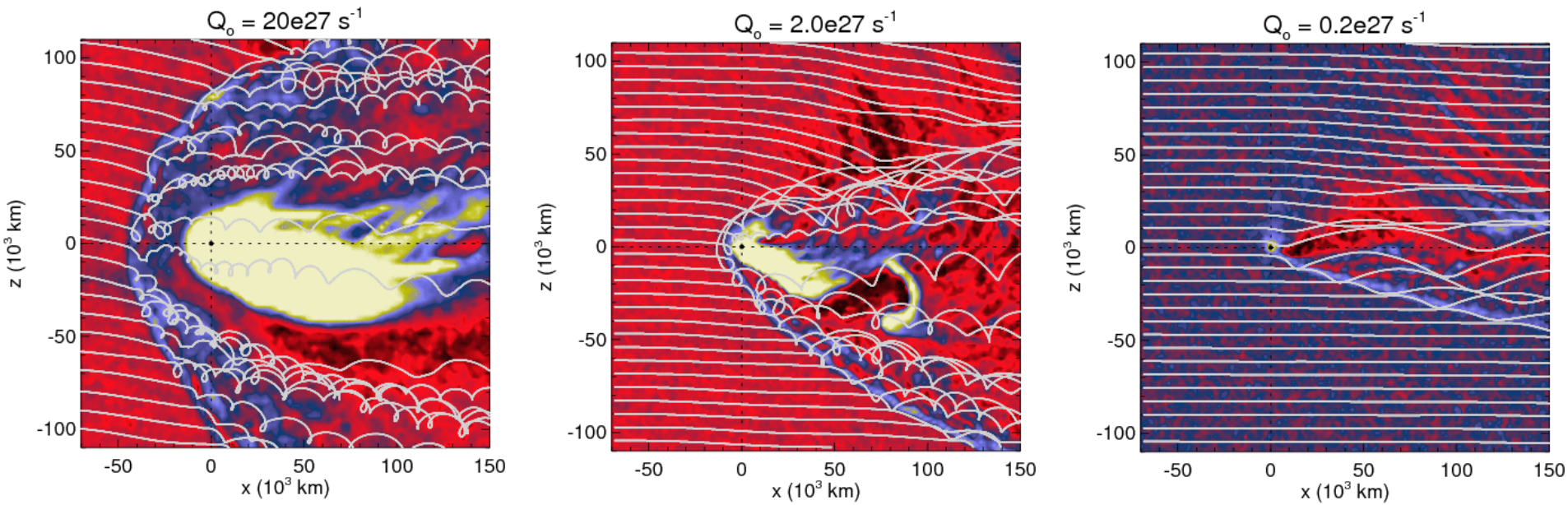


Pickup Ions



Solar Wind Protons

Proton gyromotion

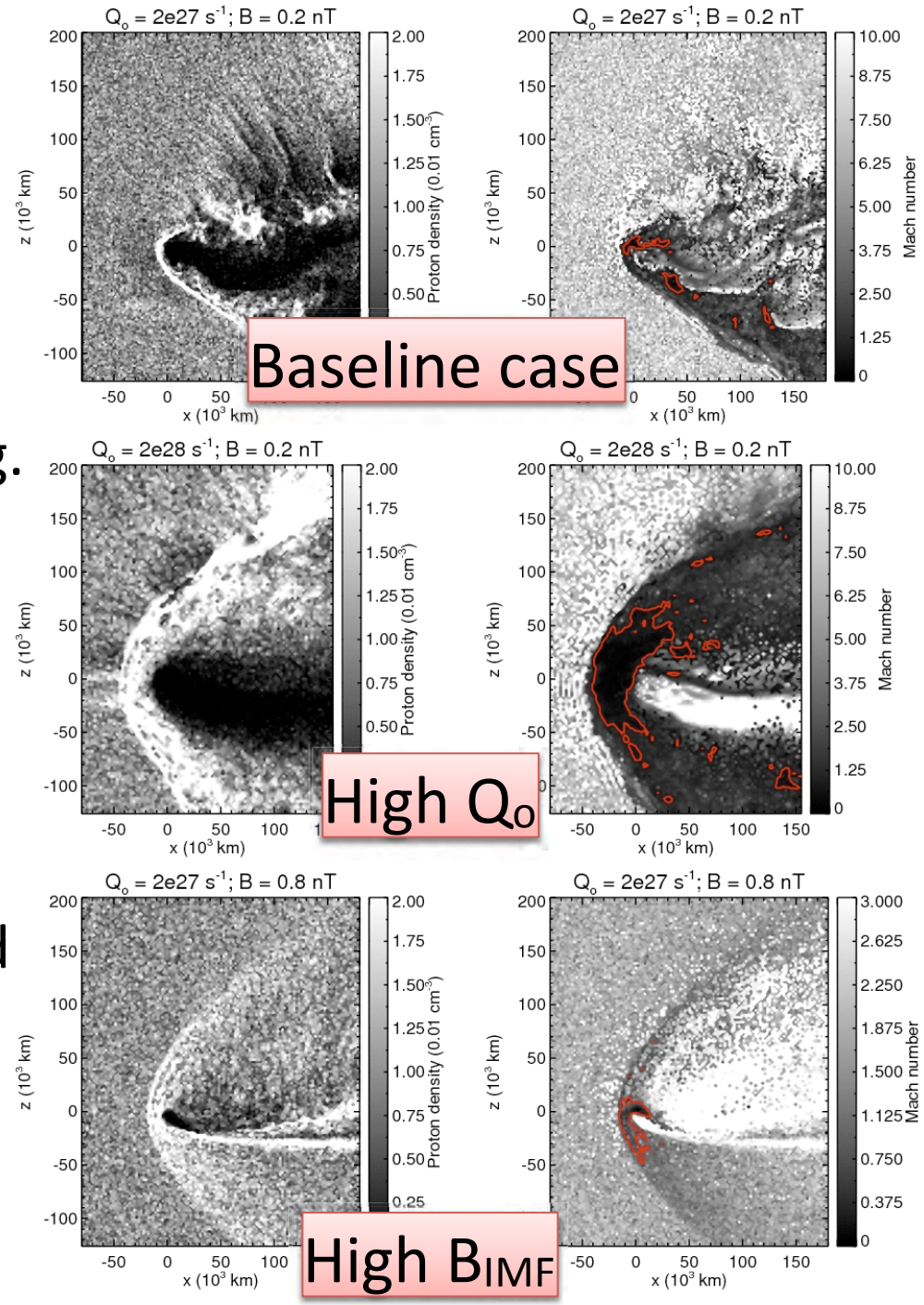


Pluto's bow shock

- Bow shock standoff distance is much closer than given by theory, e.g.

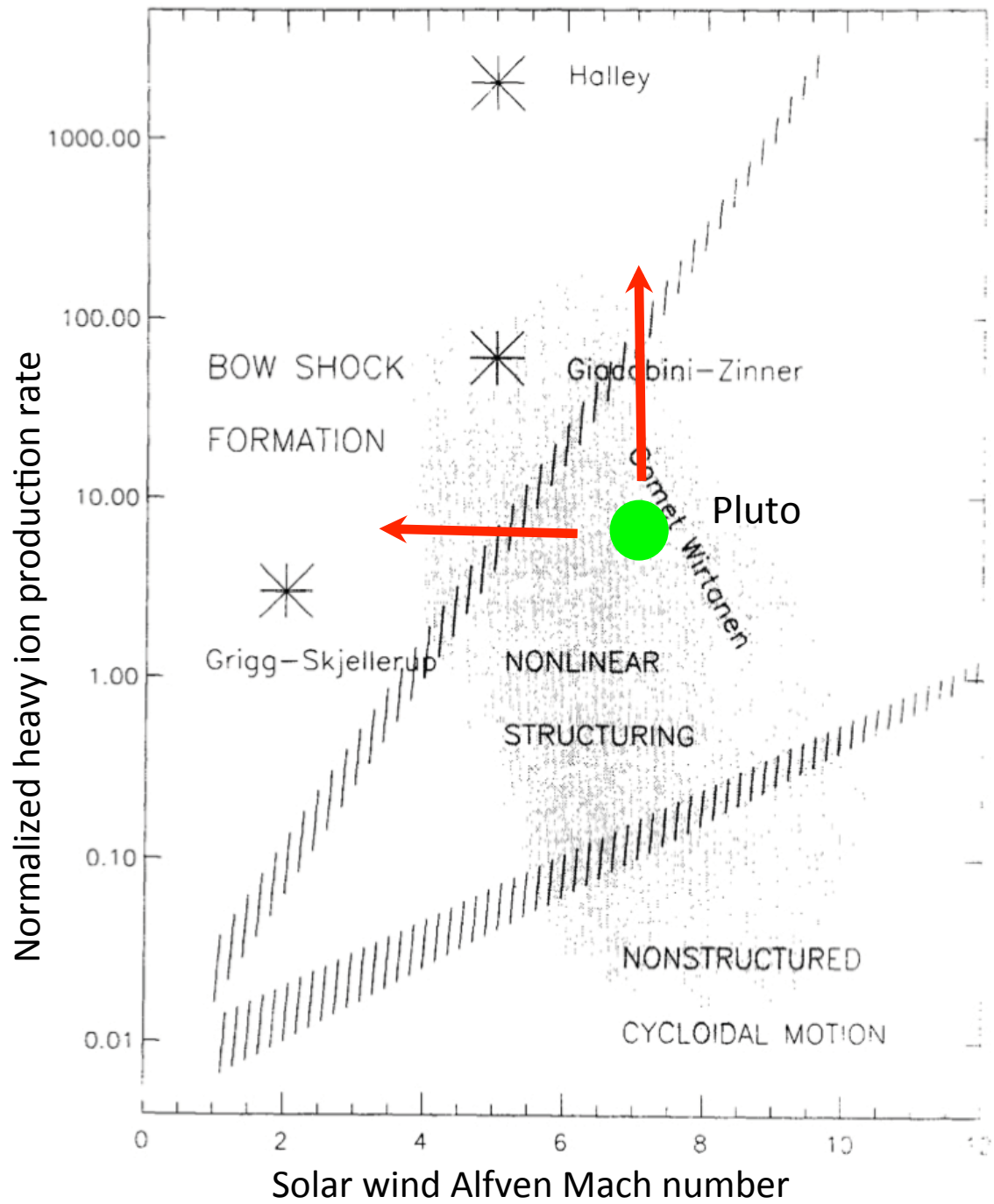
$$R_s = \frac{Q_n m_i}{4\pi v_{esc} \tau \rho_\infty u_\infty [\hat{\rho}\hat{u} - 1]}$$

- Large pickup ion gyroradius displaces full pickup to ~500 Rp downstream. Solar wind contamination minimal upstream of Pluto.

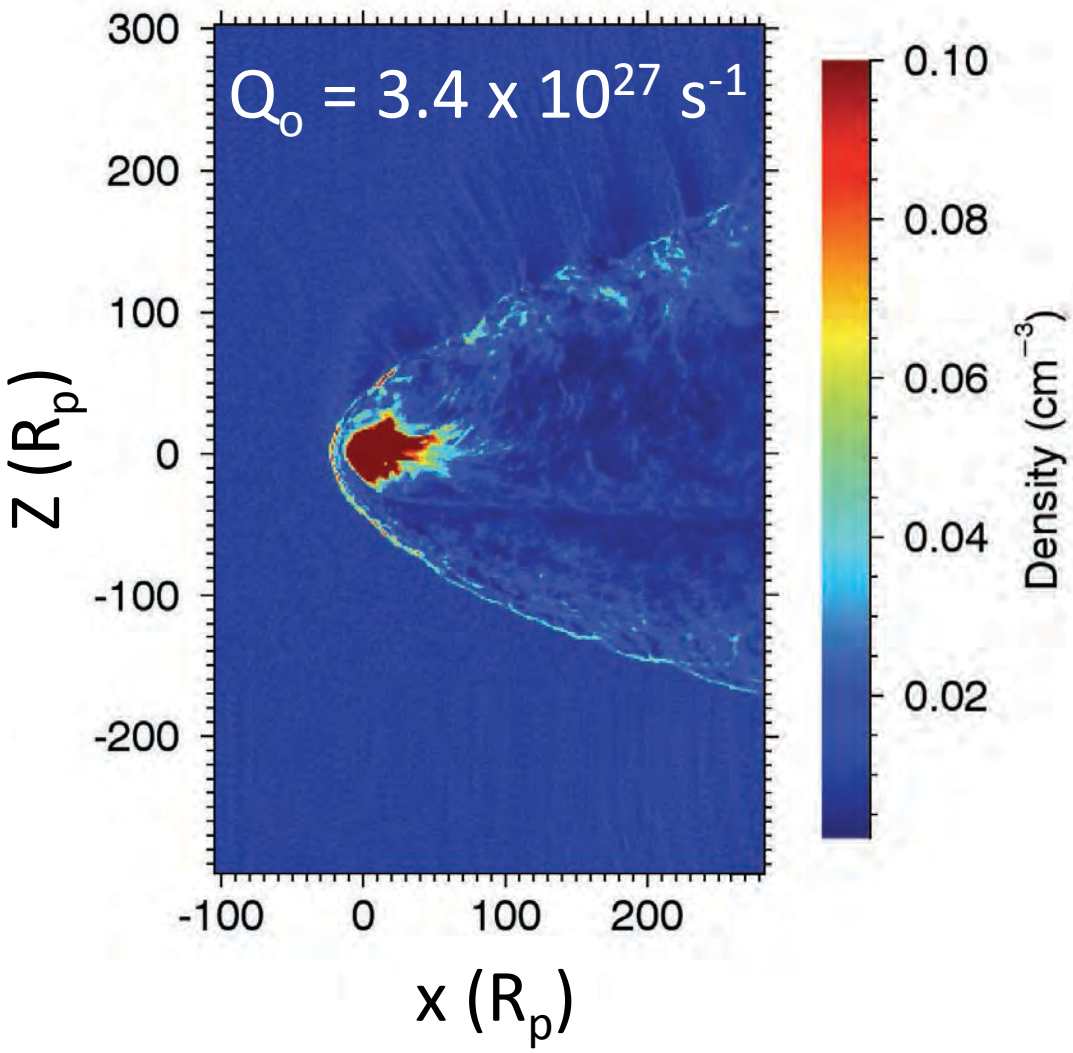


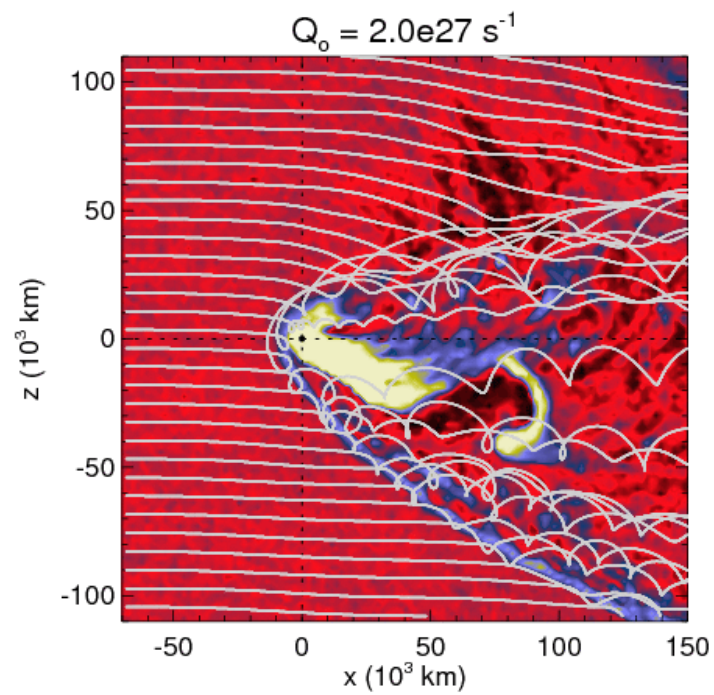
Bogdanov et al., [1996]

- Bi-ion fluid analysis of weakly outgassing comets
  - Nonlinear structuring
  - Bow shock formation
  - Nonstructured cycloidal motion

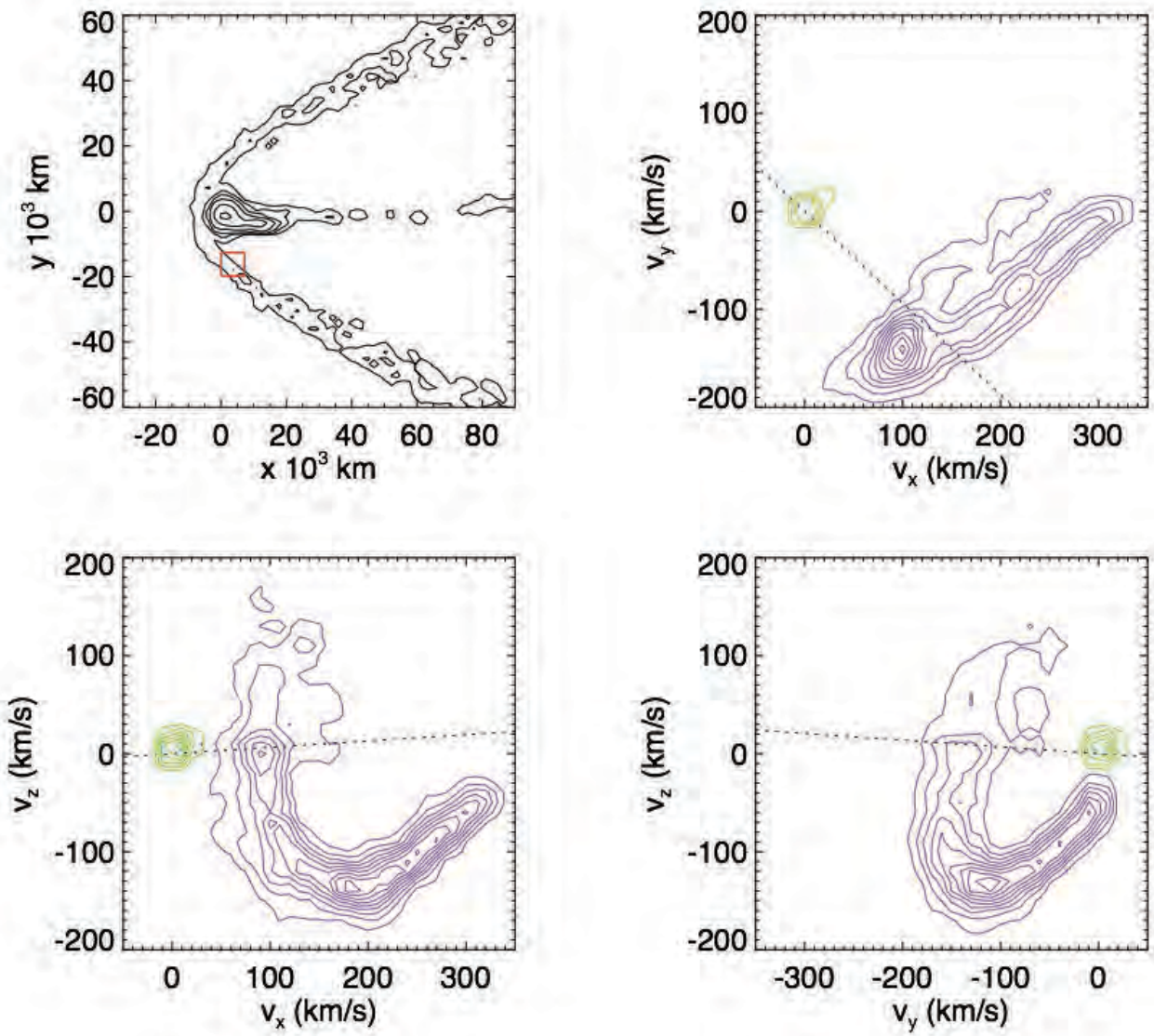


Bow shock with recent atmospheric model by *Strobel et al.*





Ion velocity distributions



Low Frequency Waves
[*Sauer et al.*, 1999]

- Electromagnetic waves at the hybrid ion cyclotron frequency ($\Omega_{p,h}$)

$$\Omega_{p,h} = \Omega_p \frac{n_h}{n} + \Omega_h \frac{n_p}{n}$$

- Beam-plasma interaction

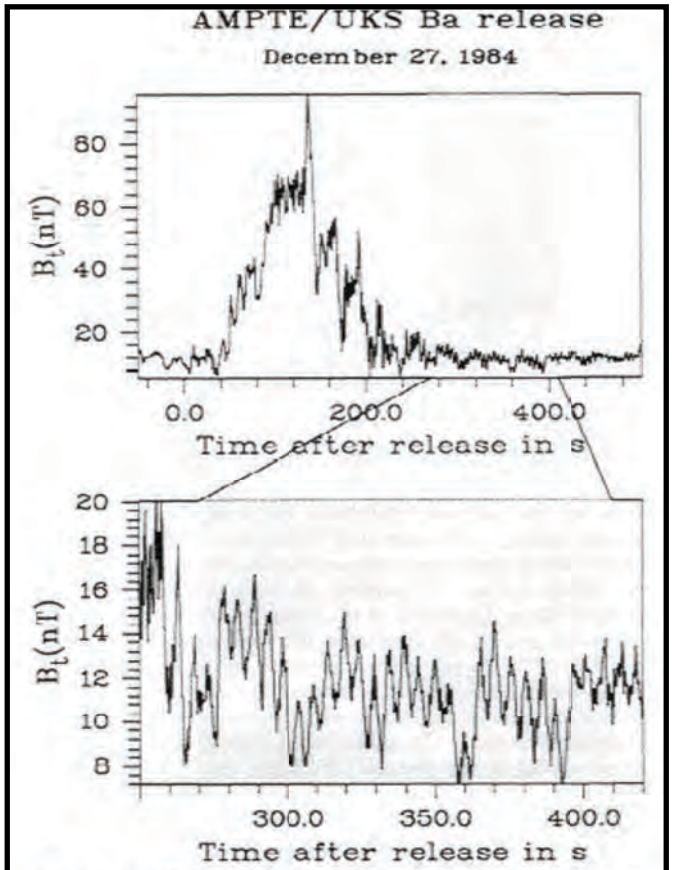
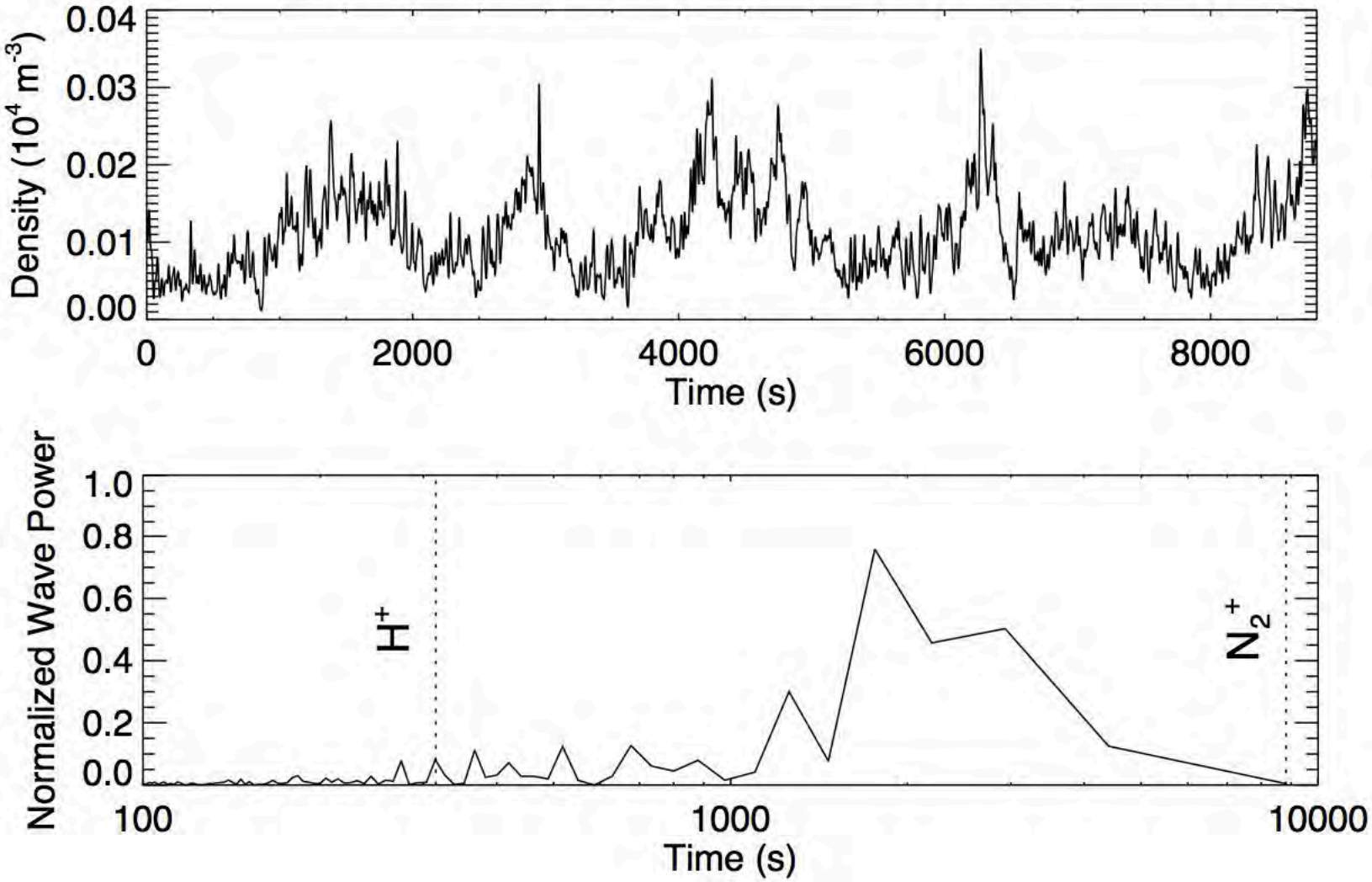
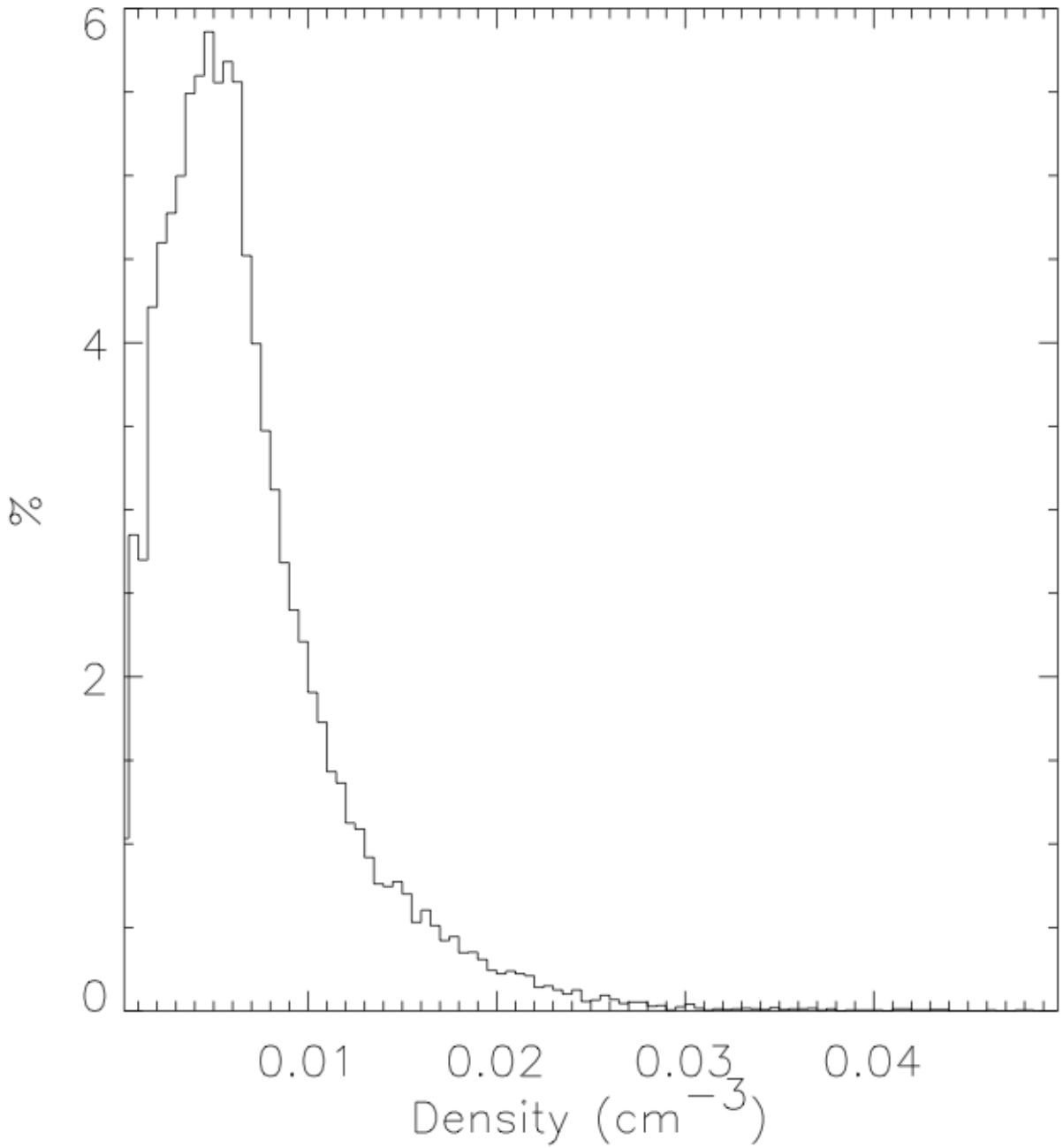
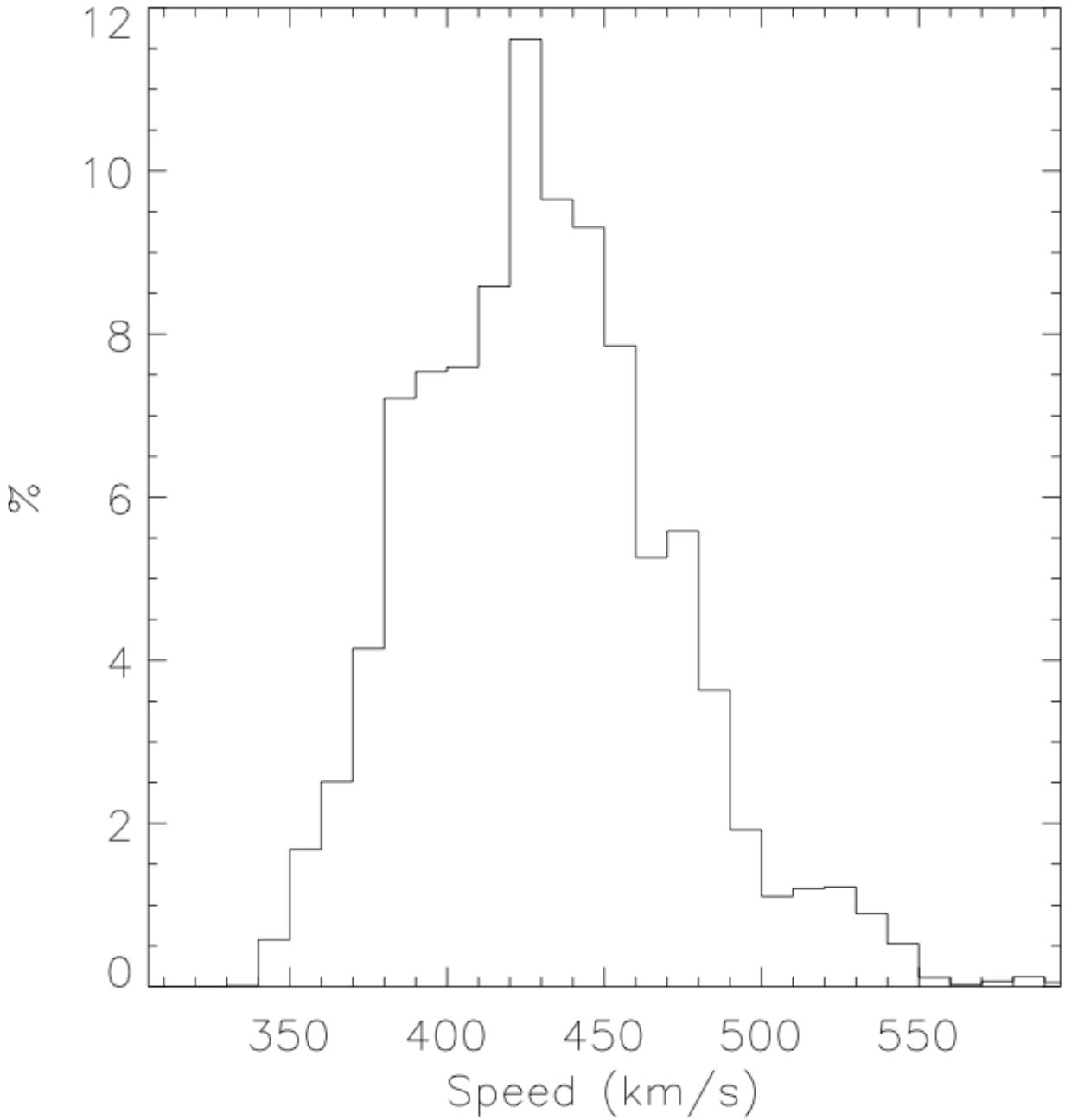


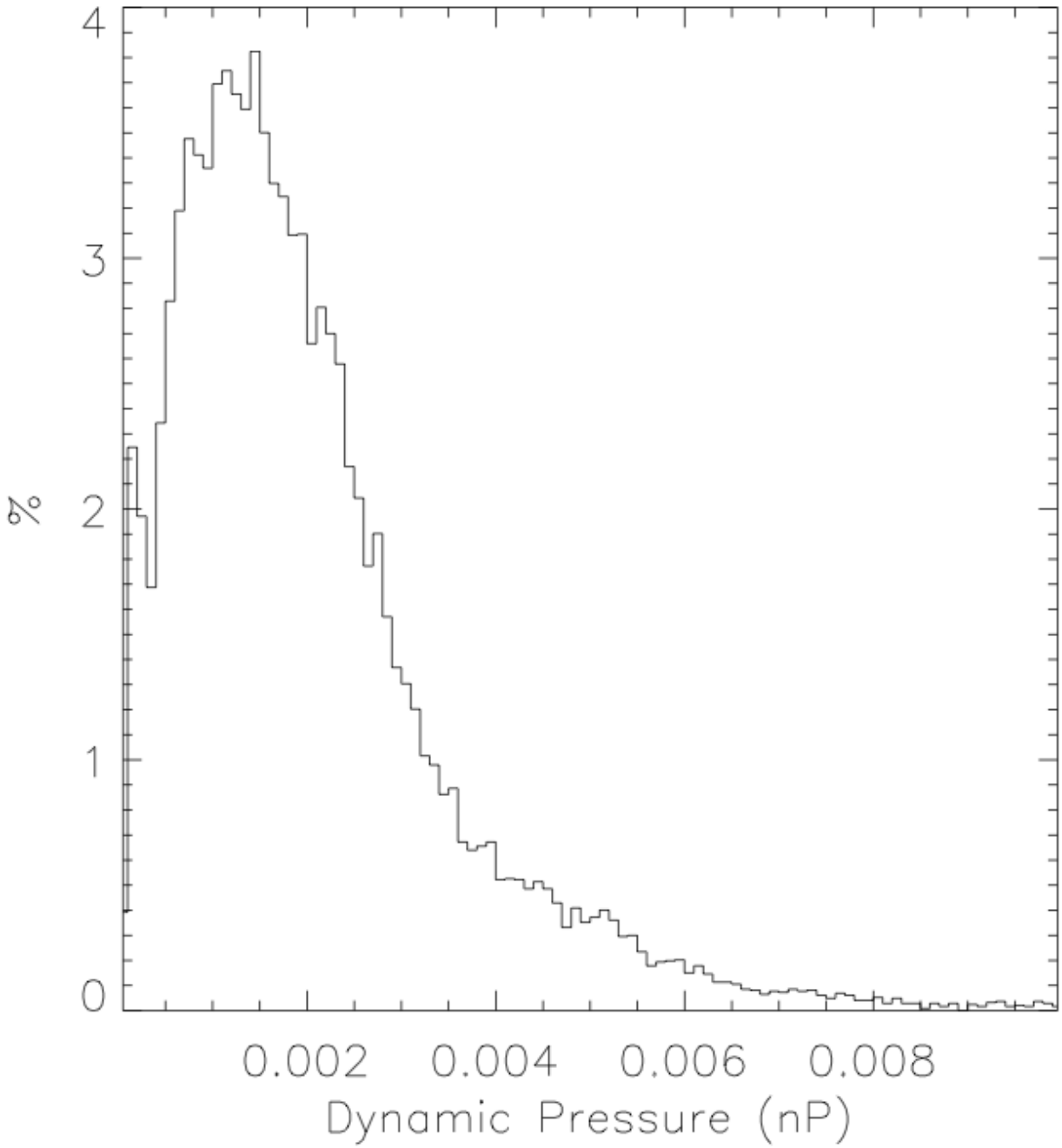
Figure 1. The magnetic field magnitude during barium release on December 27, 1984, in the solar wind.

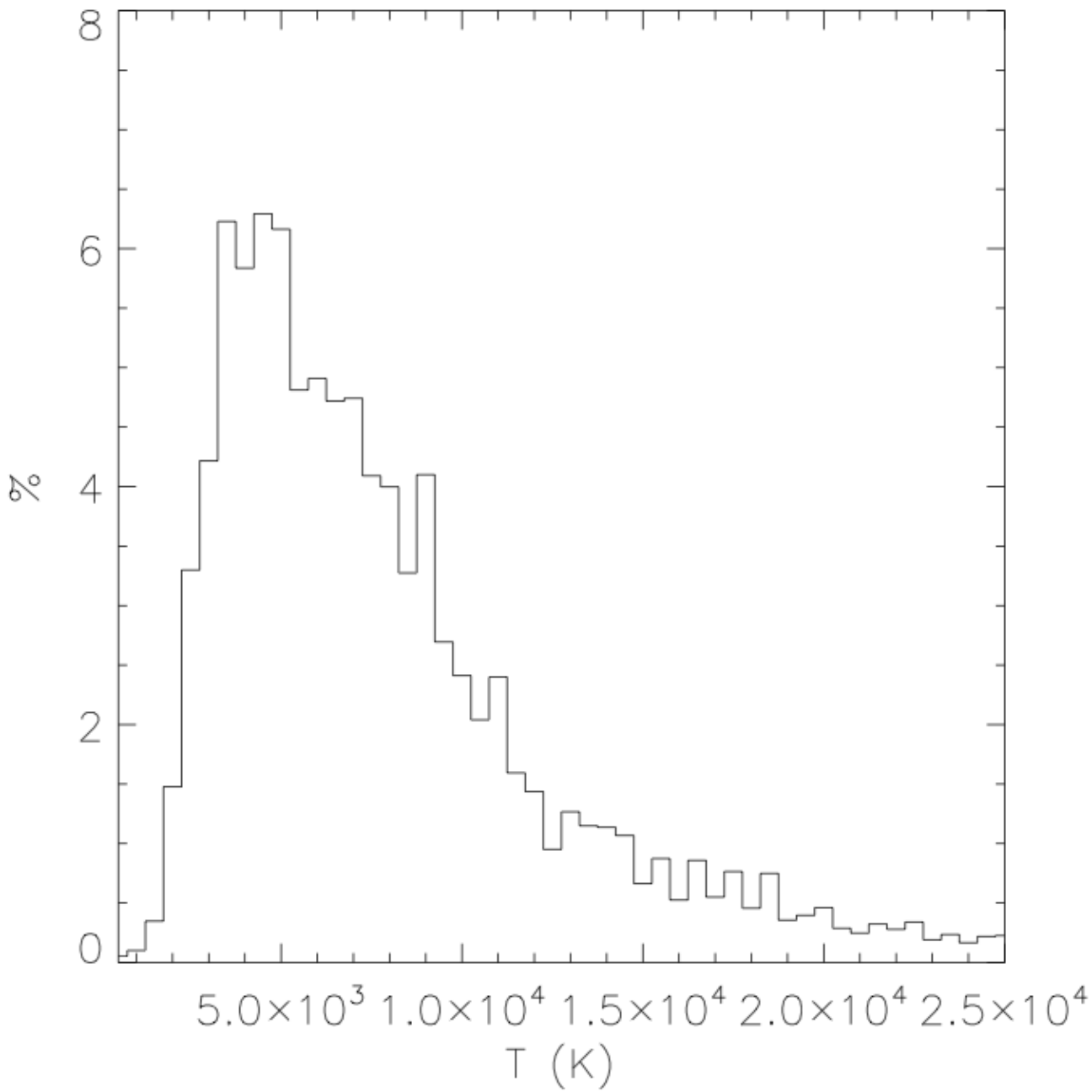
Pluto's low frequency waves

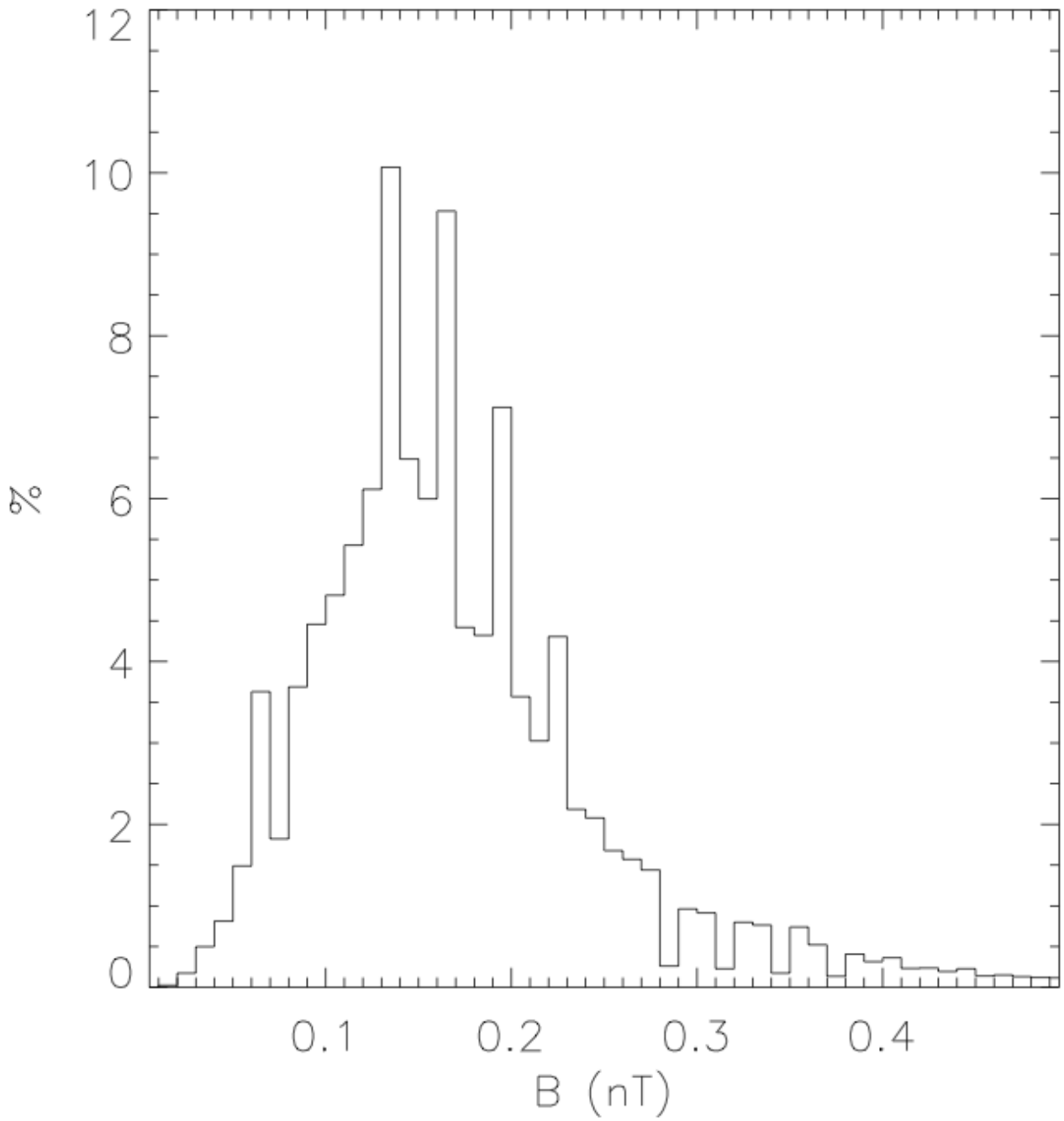


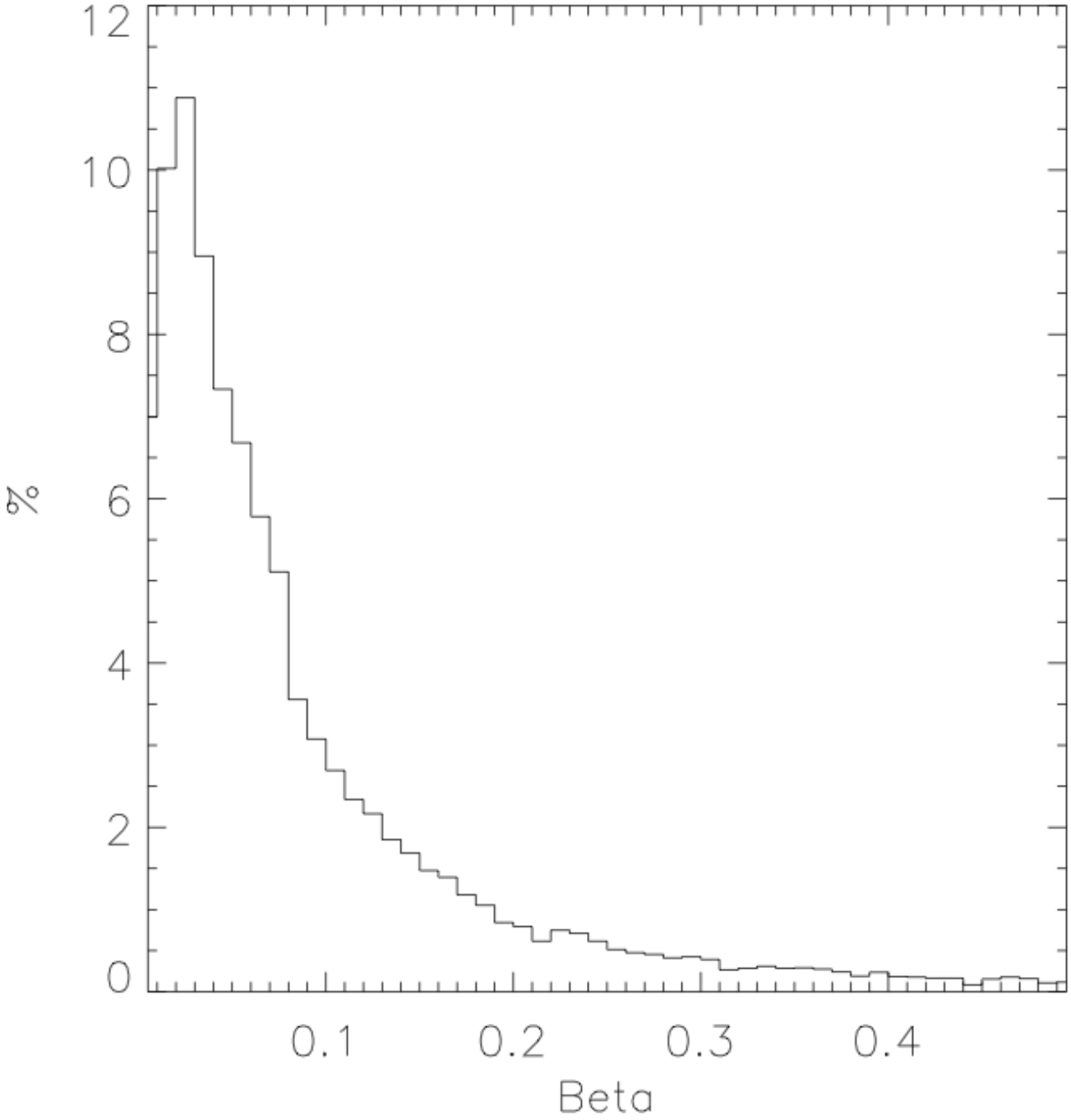

6
4
2
0
%
0.01
0.02
0.03
0.04
Density (cm^{-3})

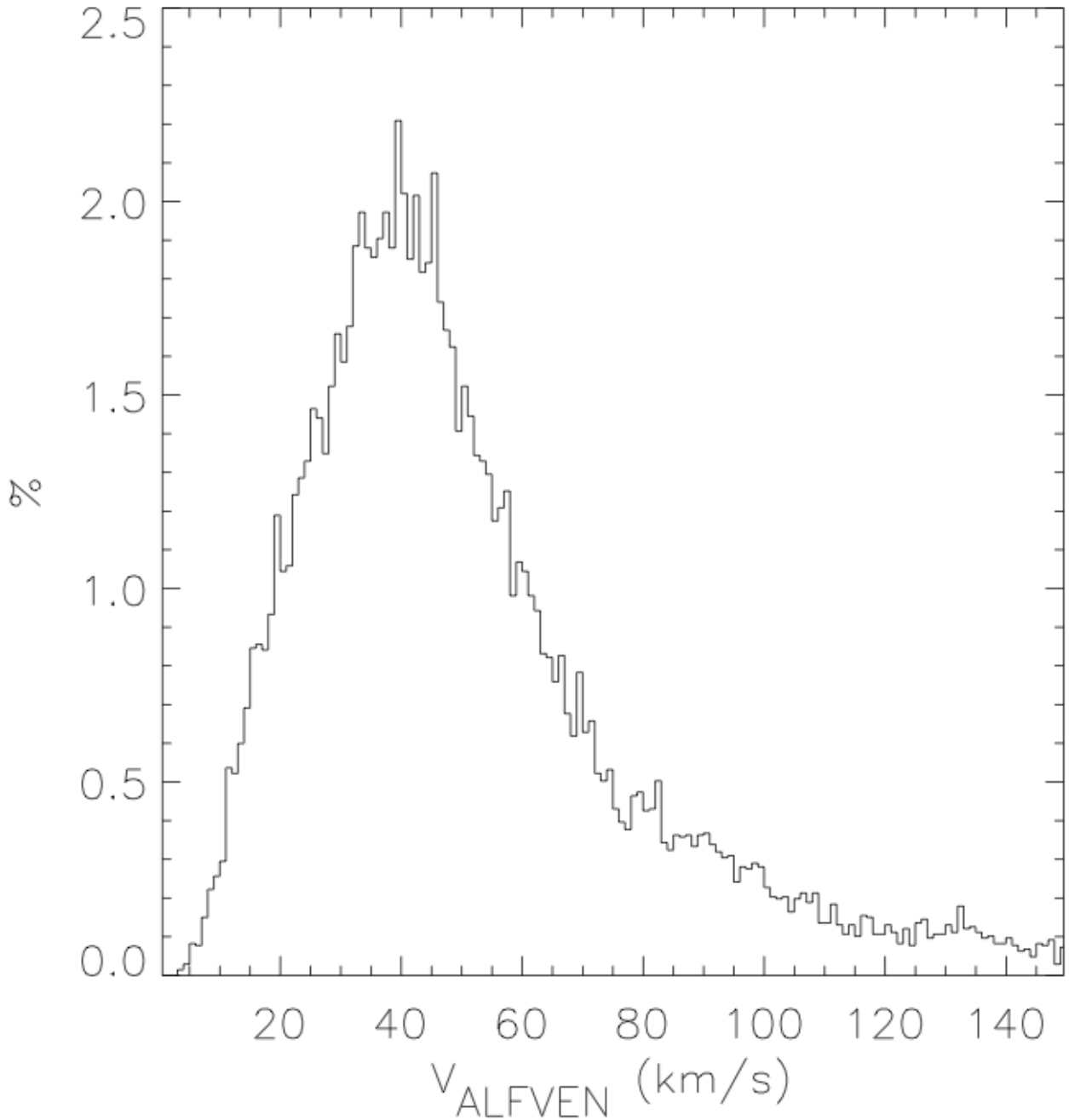

12
10
8
6
4
2
0
%
350
400
450
500
550
Speed (km/s)

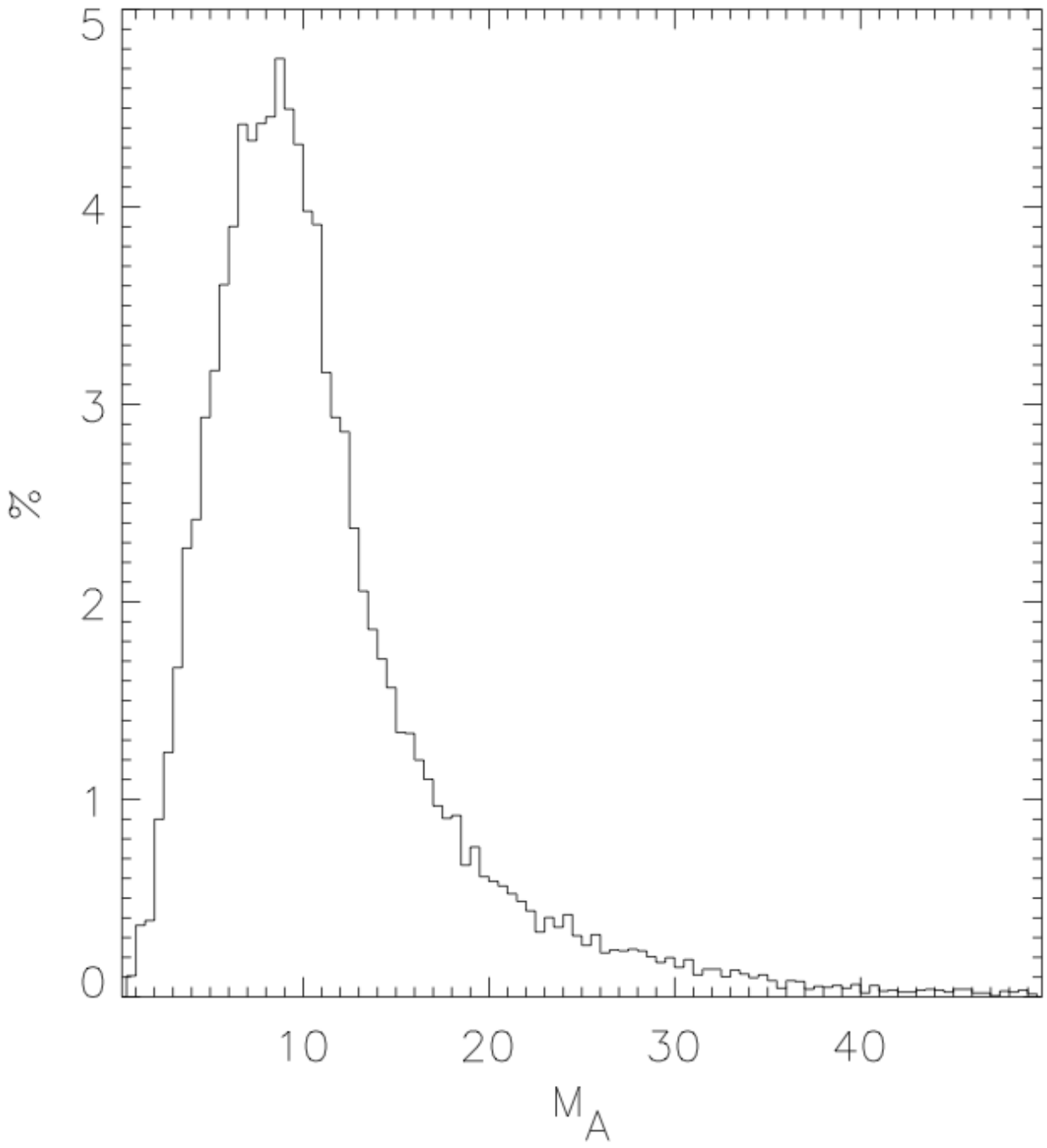

4
3
2
1
0
%
0.002
0.004
0.006
0.008
Dynamic Pressure (nP)

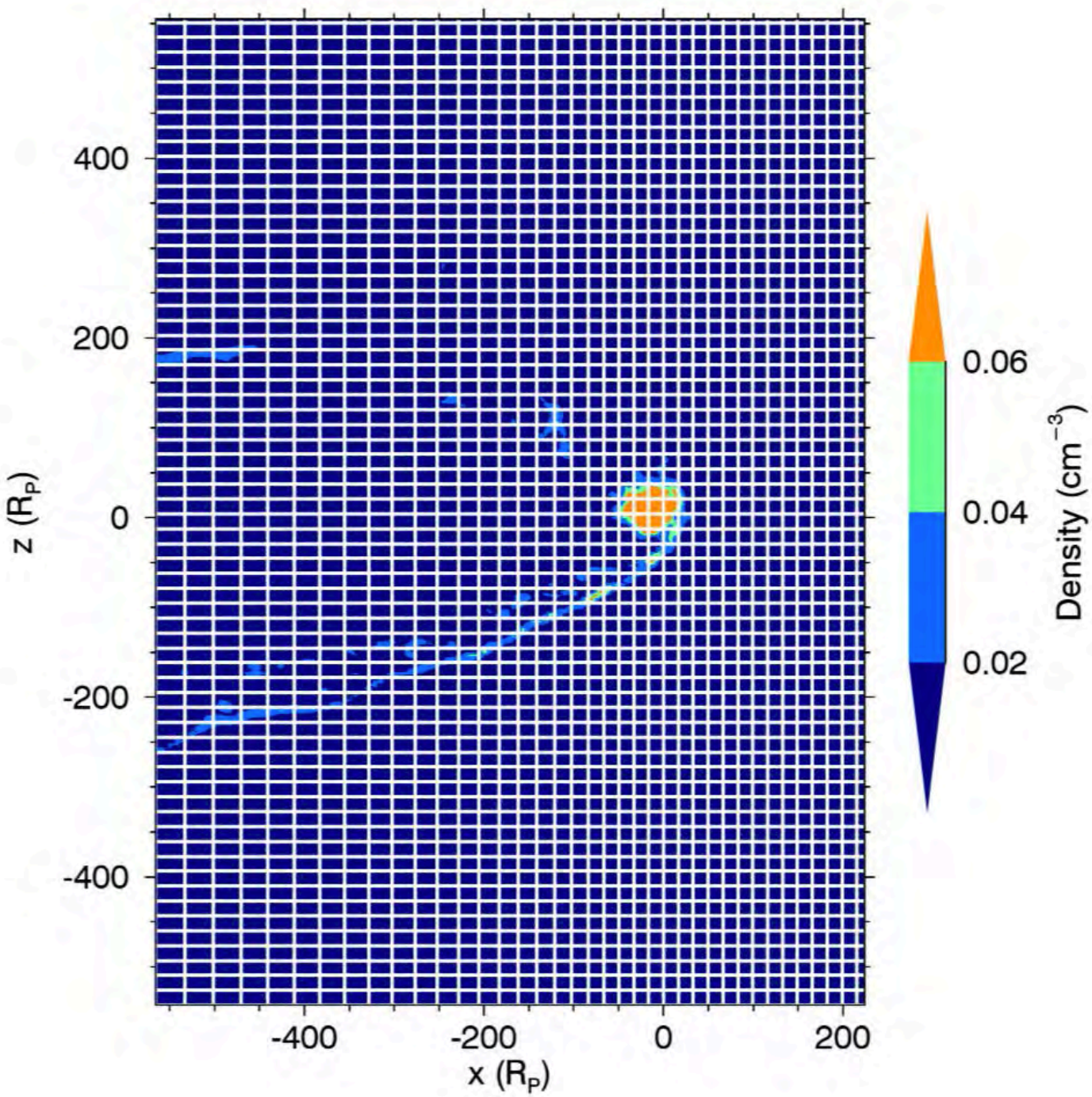

8
6
4
2
0
%
5.0×10³ 1.0×10⁴ 1.5×10⁴ 2.0×10⁴ 2.5×10⁴
T (K)


12
10
8
6
4
2
0
%
0.1
0.2
0.3
0.4
B (nT)

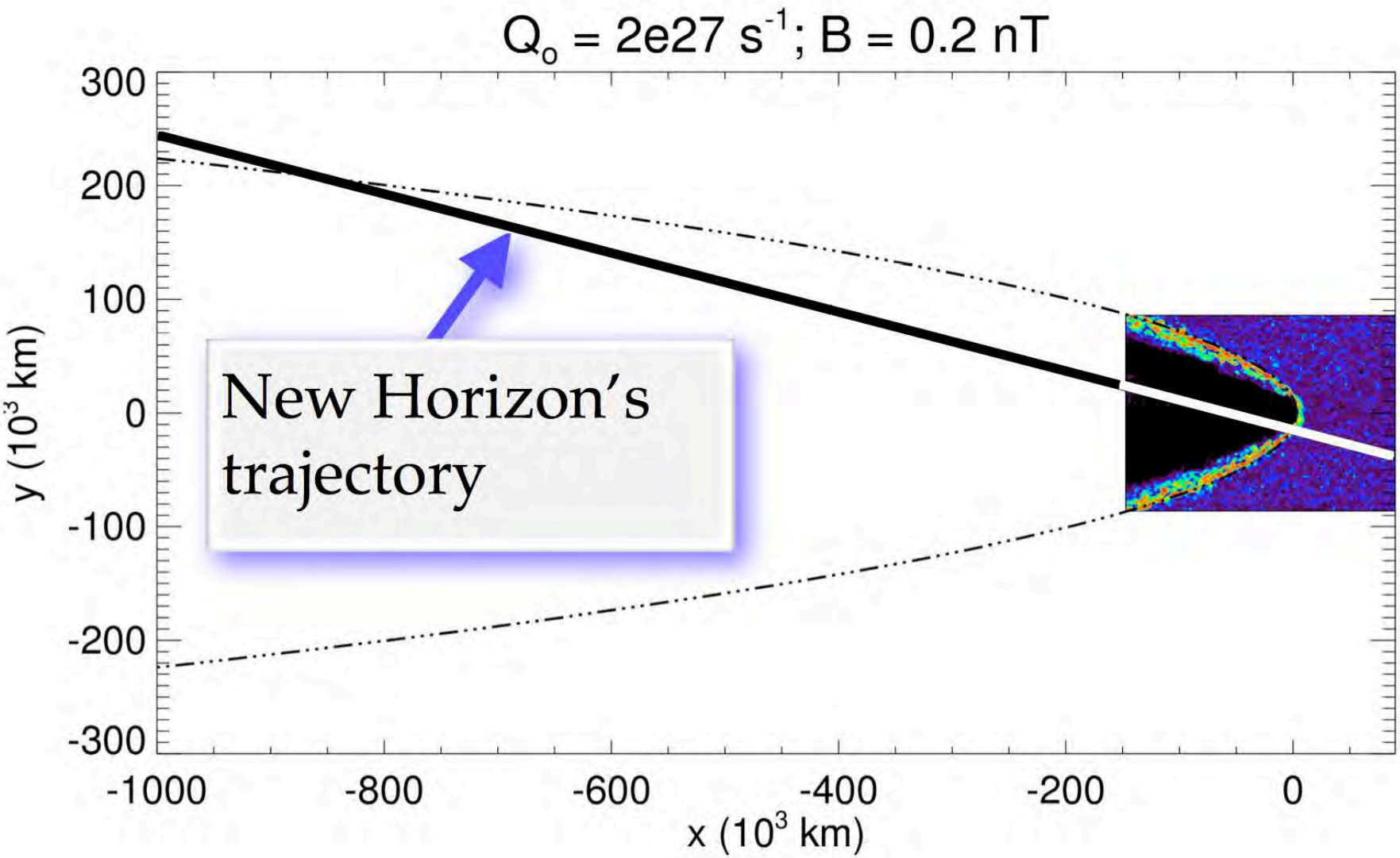

12
10
8
6
4
2
0
%
0.1
0.2
0.3
0.4
Beta


2.5
2.0
1.5
1.0
0.5
0.0
%
20
40
60
80
100
120
140
V_ALFVEN (km/s)

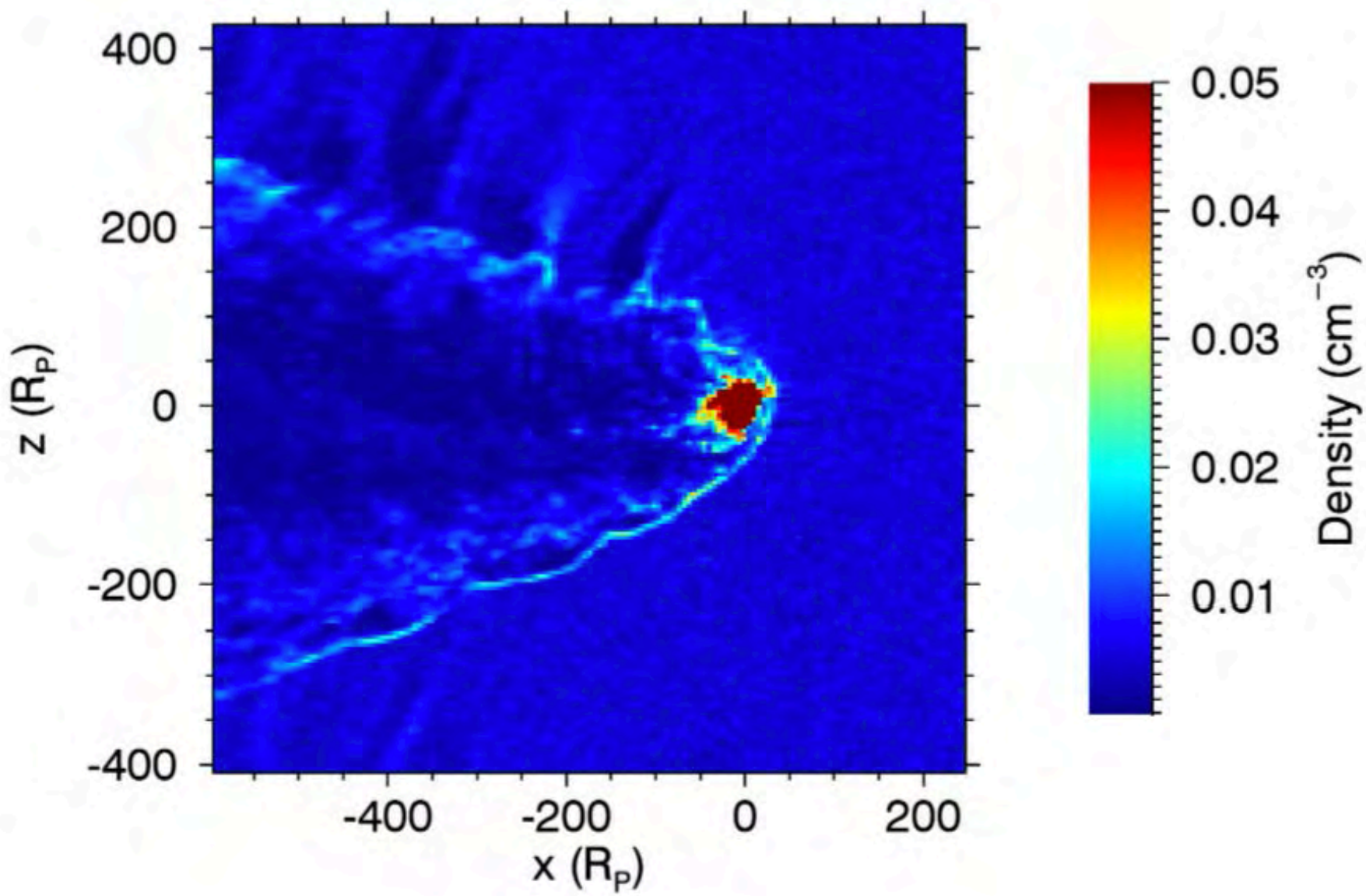

5
4
3
2
1
0
%
10
20
30
40
M_A


400
200
0
-200
-400
z (R_P)
-400
-200
0
200
x (R_P)
0.06
0.04
0.02
Density (cm^{-3})

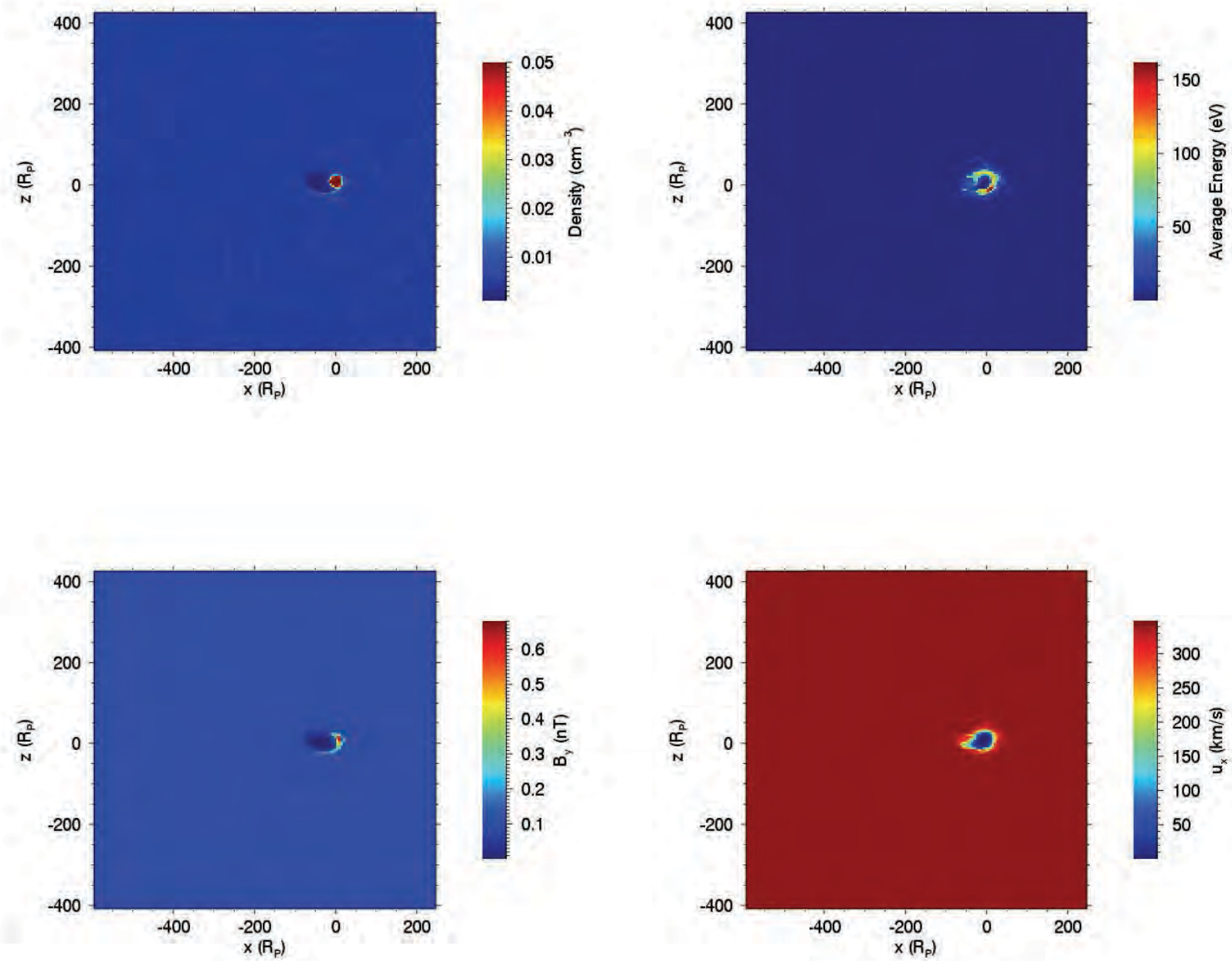
Pluto's cometary tail



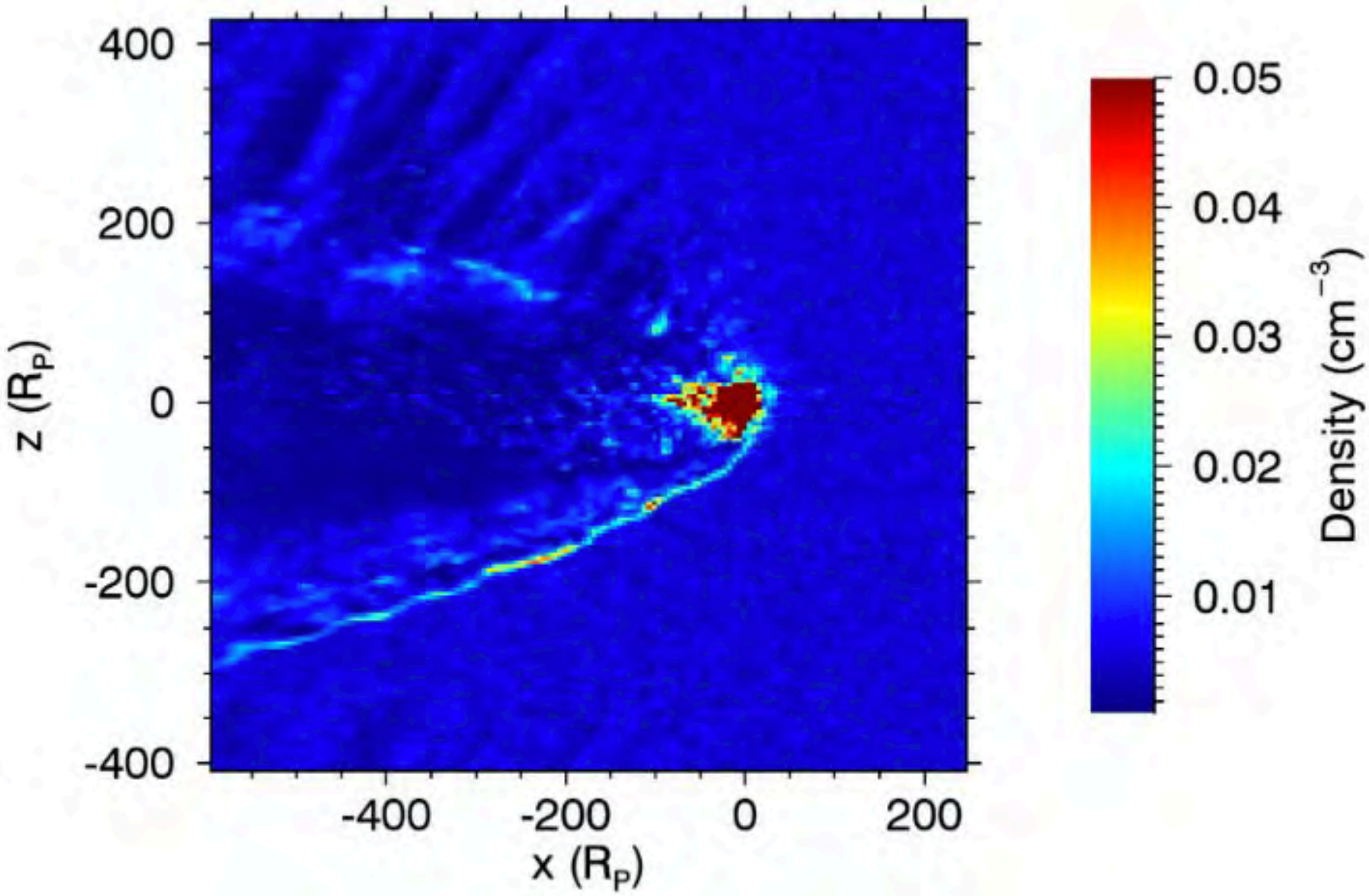
$n_{sw} = 0.005\ \mathrm{cm}^{-3}, B = 0.1\ \mathrm{nT}, v_{sw} = 340\ \mathrm{km/s}, f(v) \rightarrow\ \mathrm{H}^{+},\ \mathrm{He}^{++},\ \mathrm{PU}$



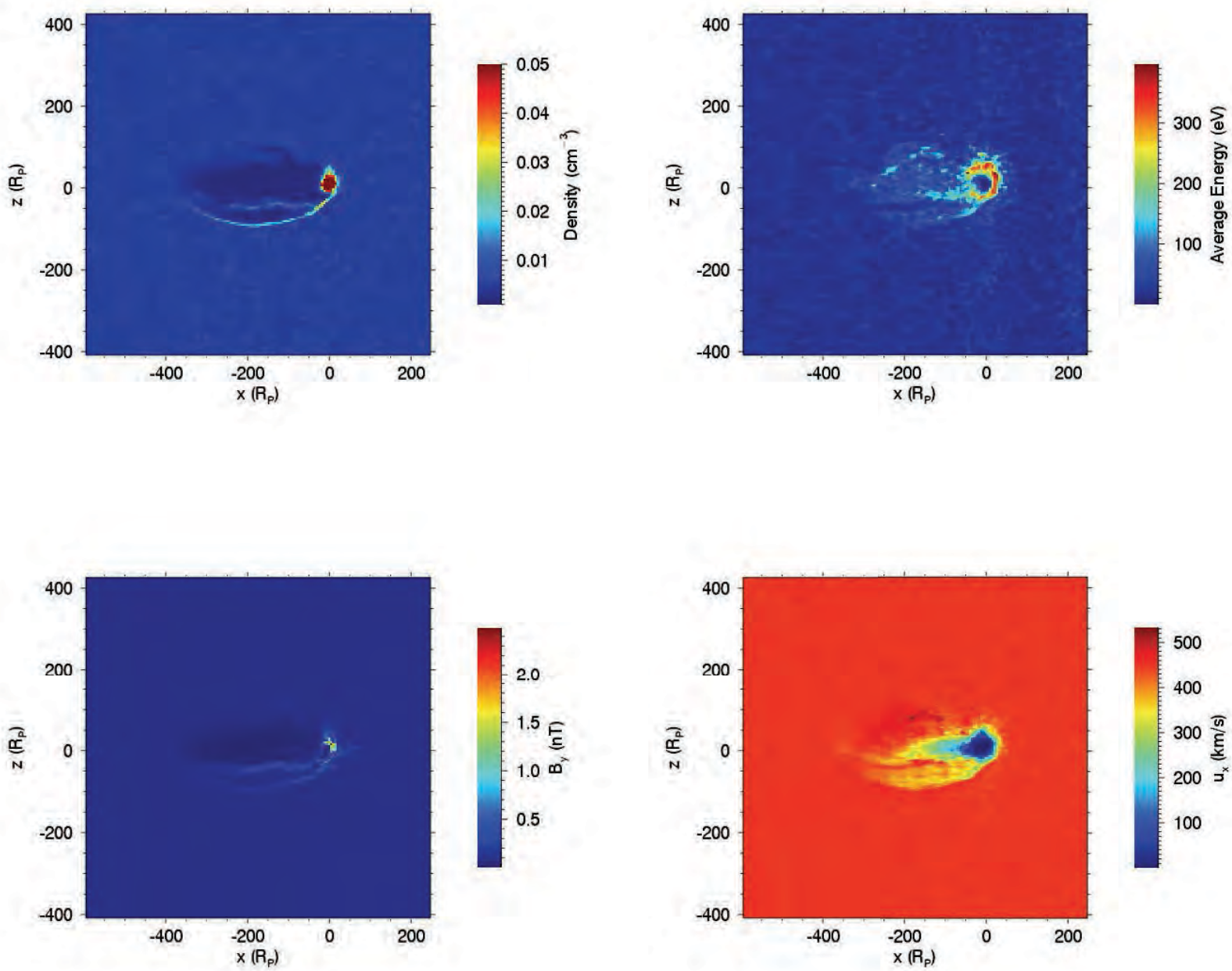
$$n_{sw} = 0.005\ \mathrm{cm}^{-3}, B = 0.1\ \mathrm{nT}, v_{sw} = 340\ \mathrm{km/s}, f(v) \rightarrow\ \mathrm{H}^{+},\ \mathrm{He}^{++},\ \mathrm{PU}$$



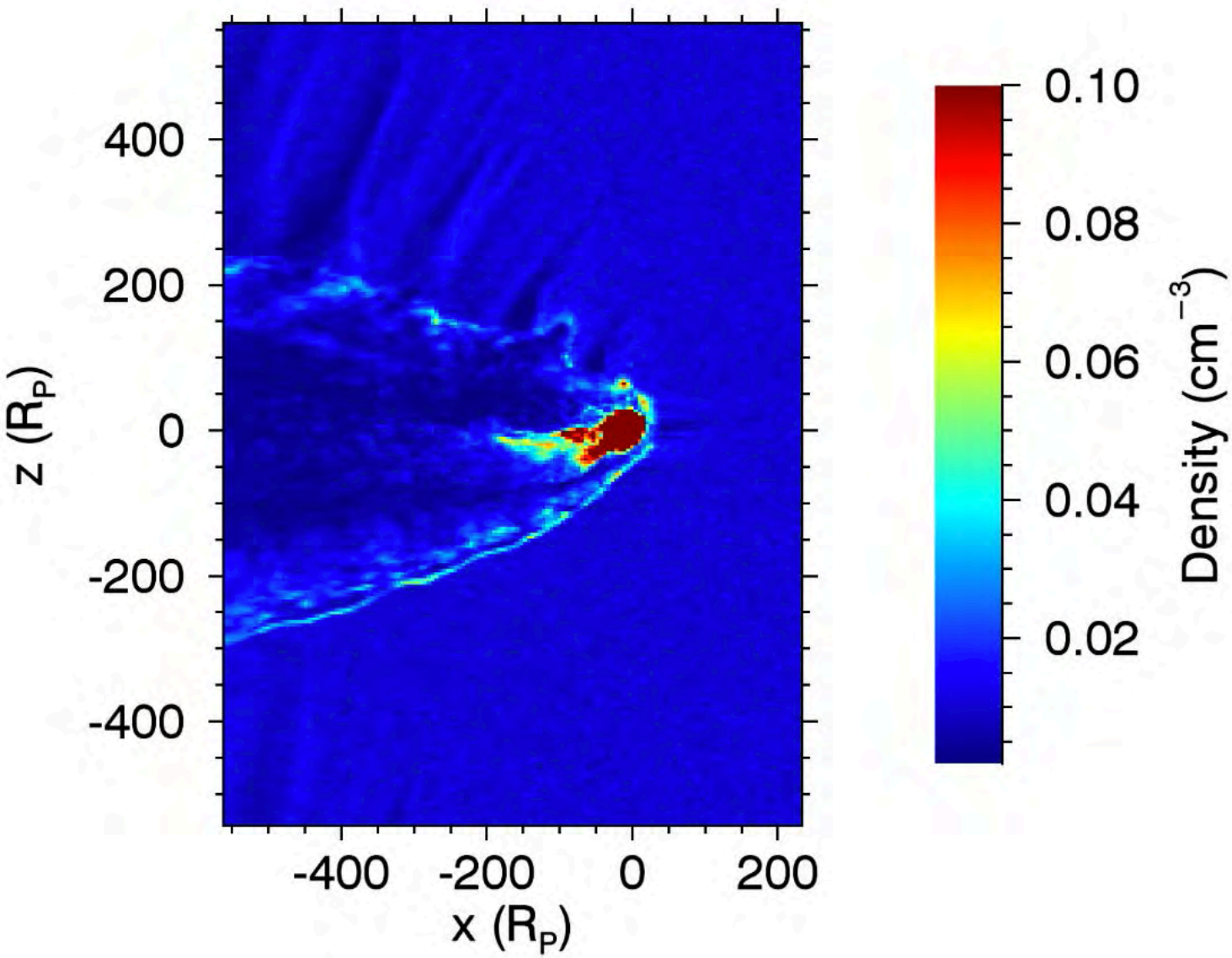
$n_{sw} = 0.005\ \mathrm{cm}^{-3}, B = 0.1\ \mathrm{nT}, v_{sw} = 450\ \mathrm{km/s}, f(v) \rightarrow\ \mathrm{H}^{+},\ \mathrm{He}^{++},\ \mathrm{PU}$



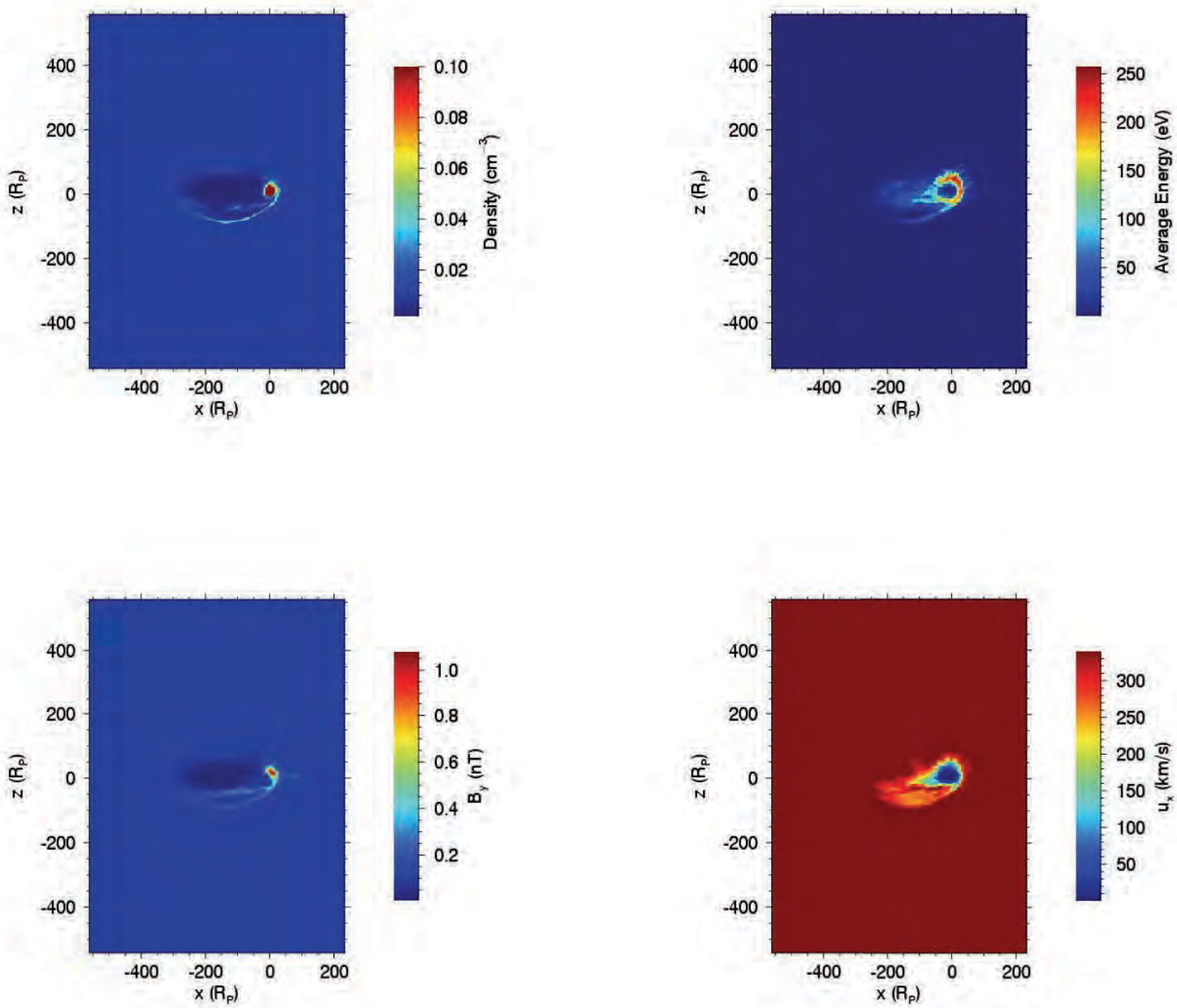
$$n_{sw} = 0.005\ \mathrm{cm}^{-3}, B = 0.1\ \mathrm{nT}, v_{sw} = 450\ \mathrm{km/s}, f(v) \rightarrow\ \mathrm{H}^{+},\ \mathrm{He}^{++},\ \mathrm{PU}$$



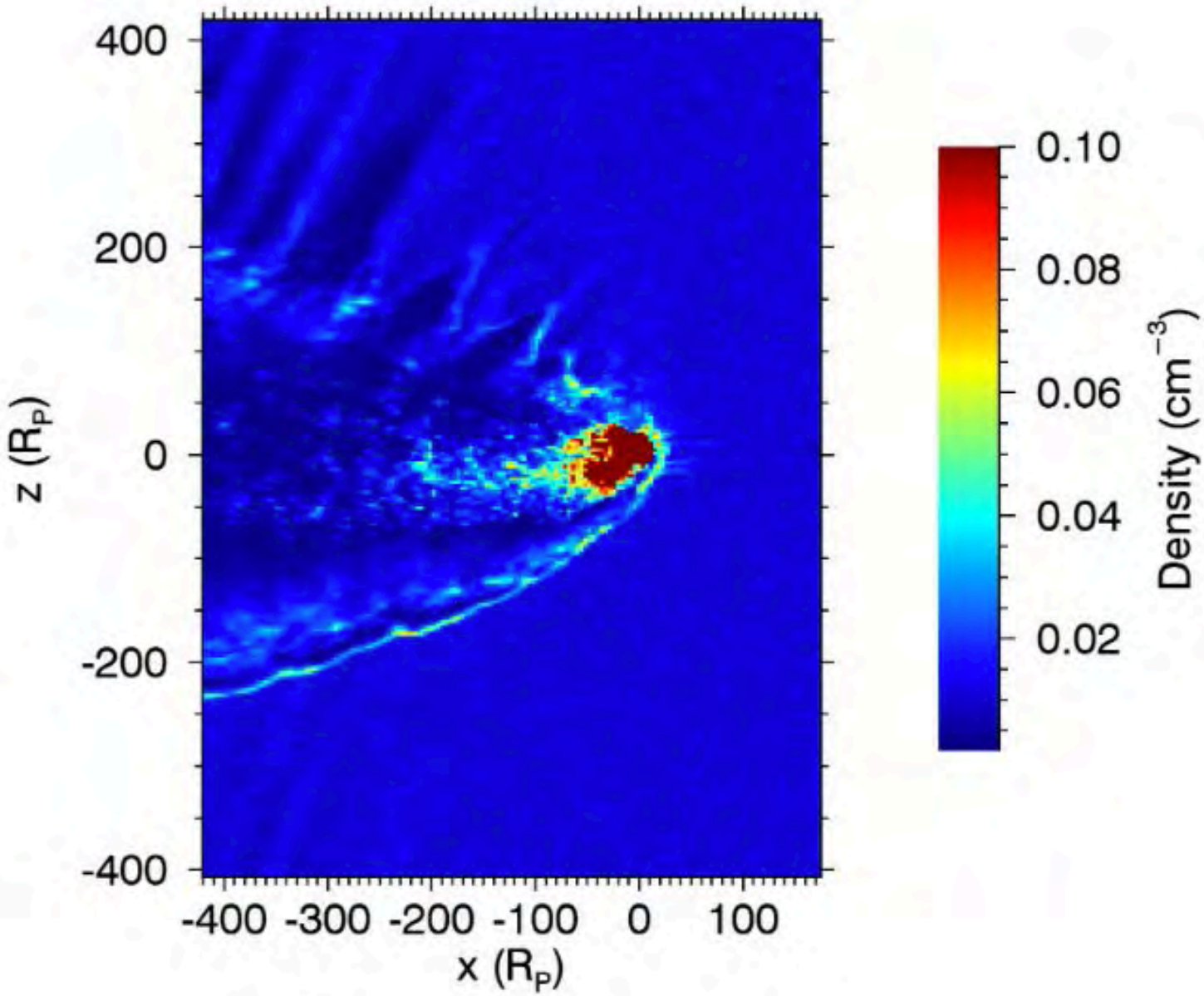
$n_{sw} = 0.01\ \mathrm{cm}^{-3}, B = 0.1\ \mathrm{nT}, v_{sw} = 340\ \mathrm{km/s}, f(v) \rightarrow\ \mathrm{H}^{+},\ \mathrm{He}^{++}$



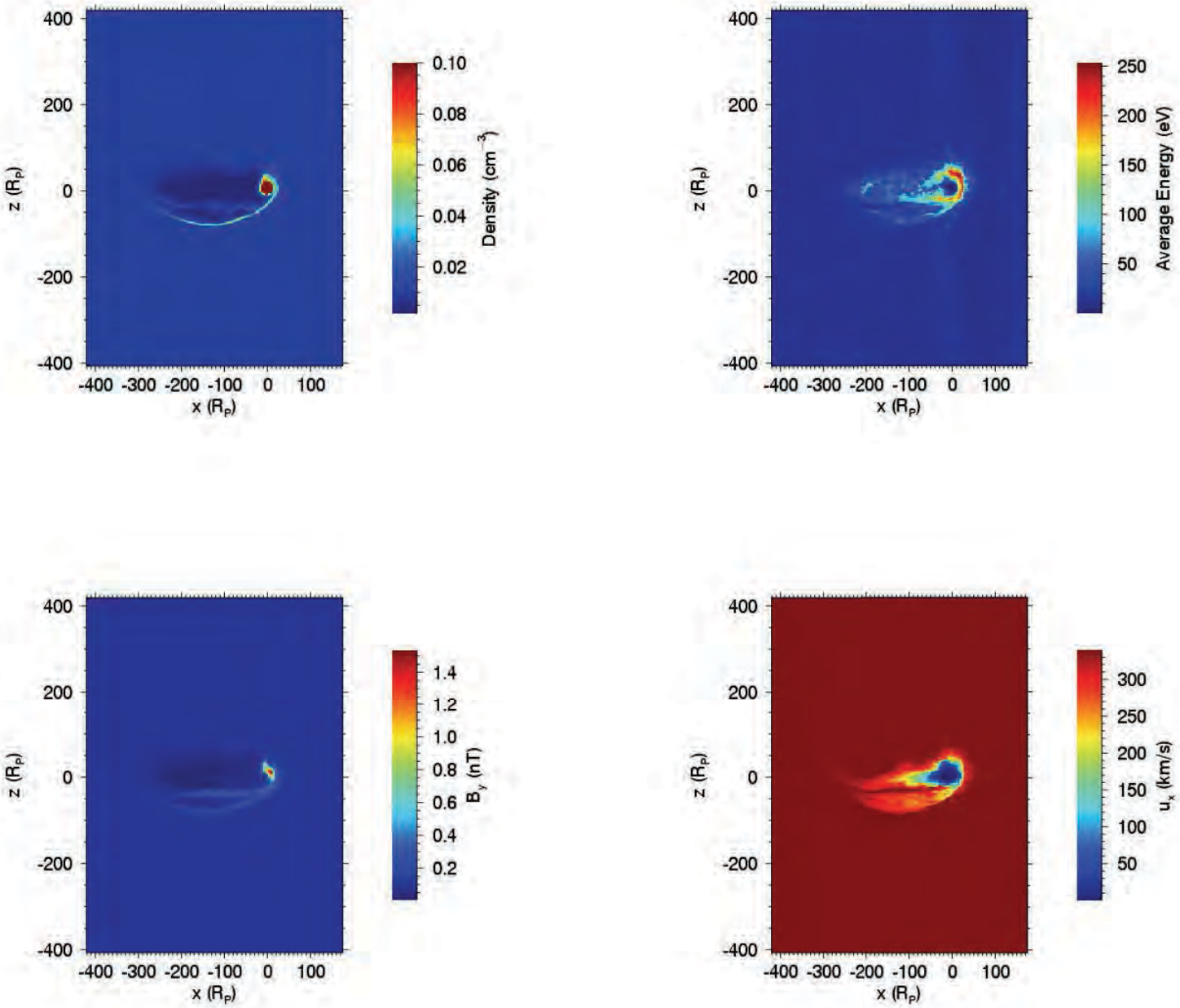
$$n_{sw} = 0.01\ \mathrm{cm}^{-3}, B = 0.1\ \mathrm{nT}, v_{sw} = 340\ \mathrm{km/s}, f(v) \rightarrow\ \mathrm{H}^{+},\ \mathrm{He}^{++}$$



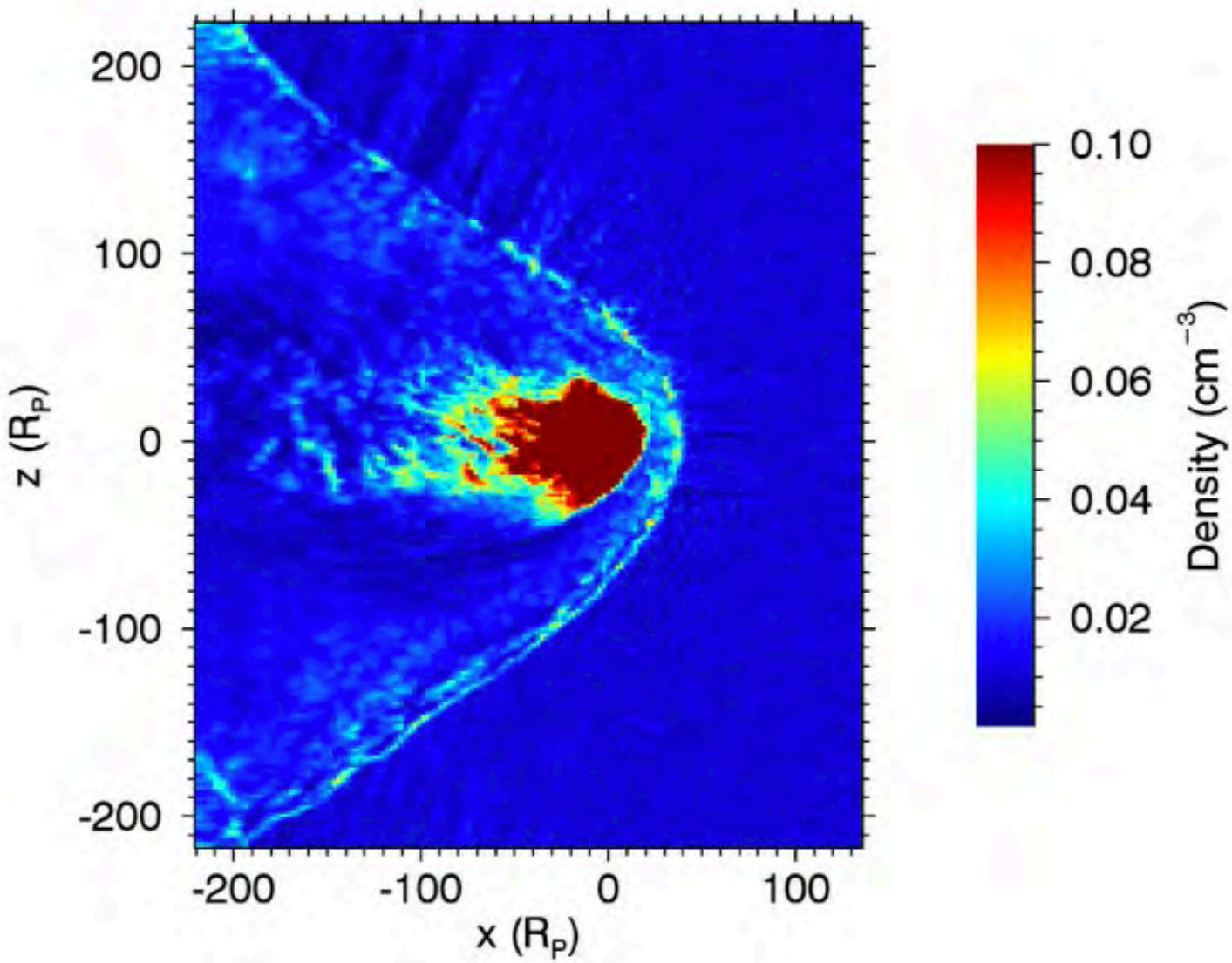
$n_{sw} = 0.01\ \mathrm{cm}^{-3}, B = 0.1\ \mathrm{nT}, v_{sw} = 340\ \mathrm{km/s}, f(v) \rightarrow\ \mathrm{H}^{+},\ \mathrm{He}^{++},\ \mathrm{PU}$



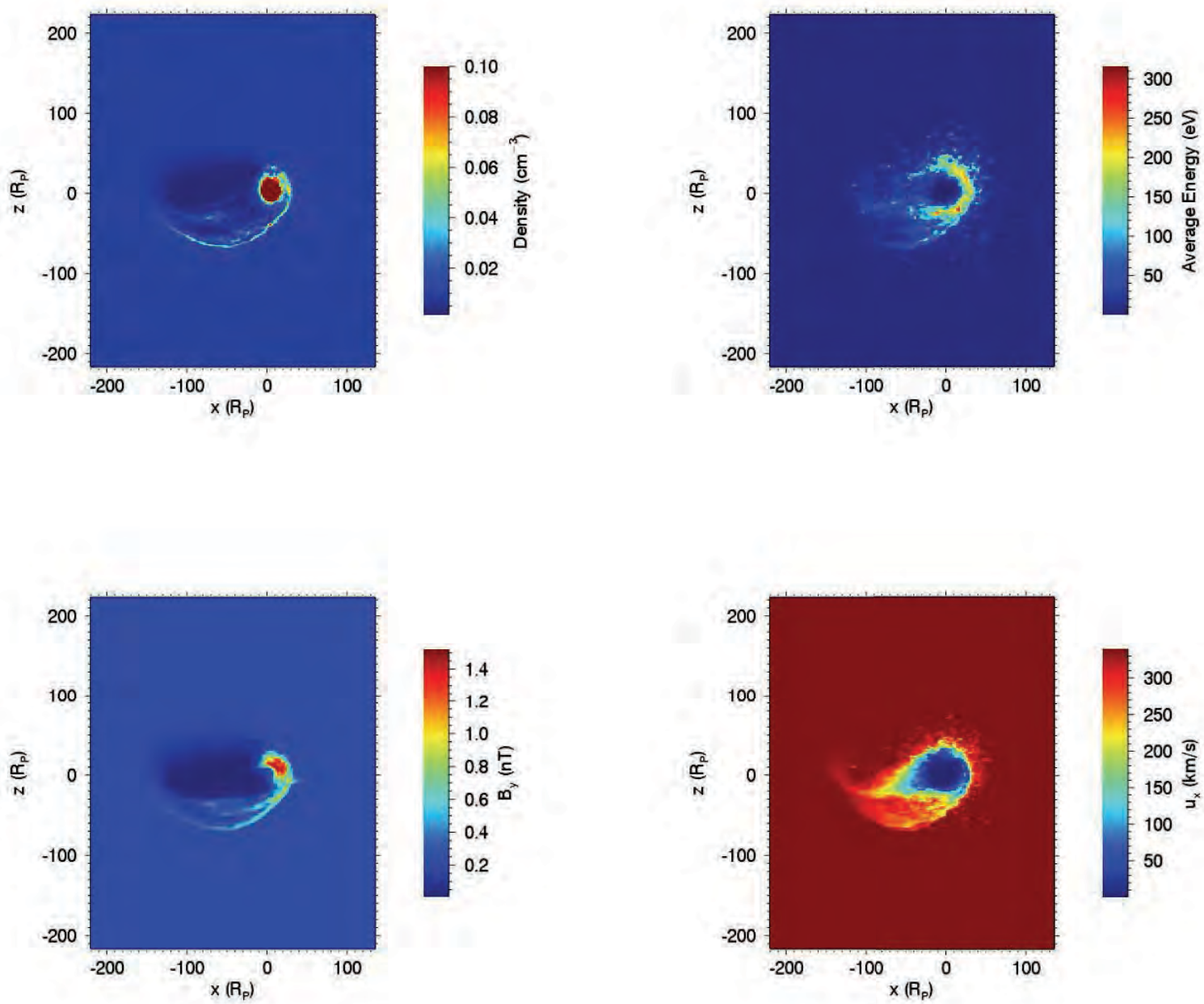
$$n_{sw} = 0.01\ \mathrm{cm}^{-3}, B = 0.1\ \mathrm{nT}, v_{sw} = 340\ \mathrm{km/s}, f(v) \rightarrow\ \mathrm{H}^{+},\ \mathrm{He}^{++},\ \mathrm{PU}$$



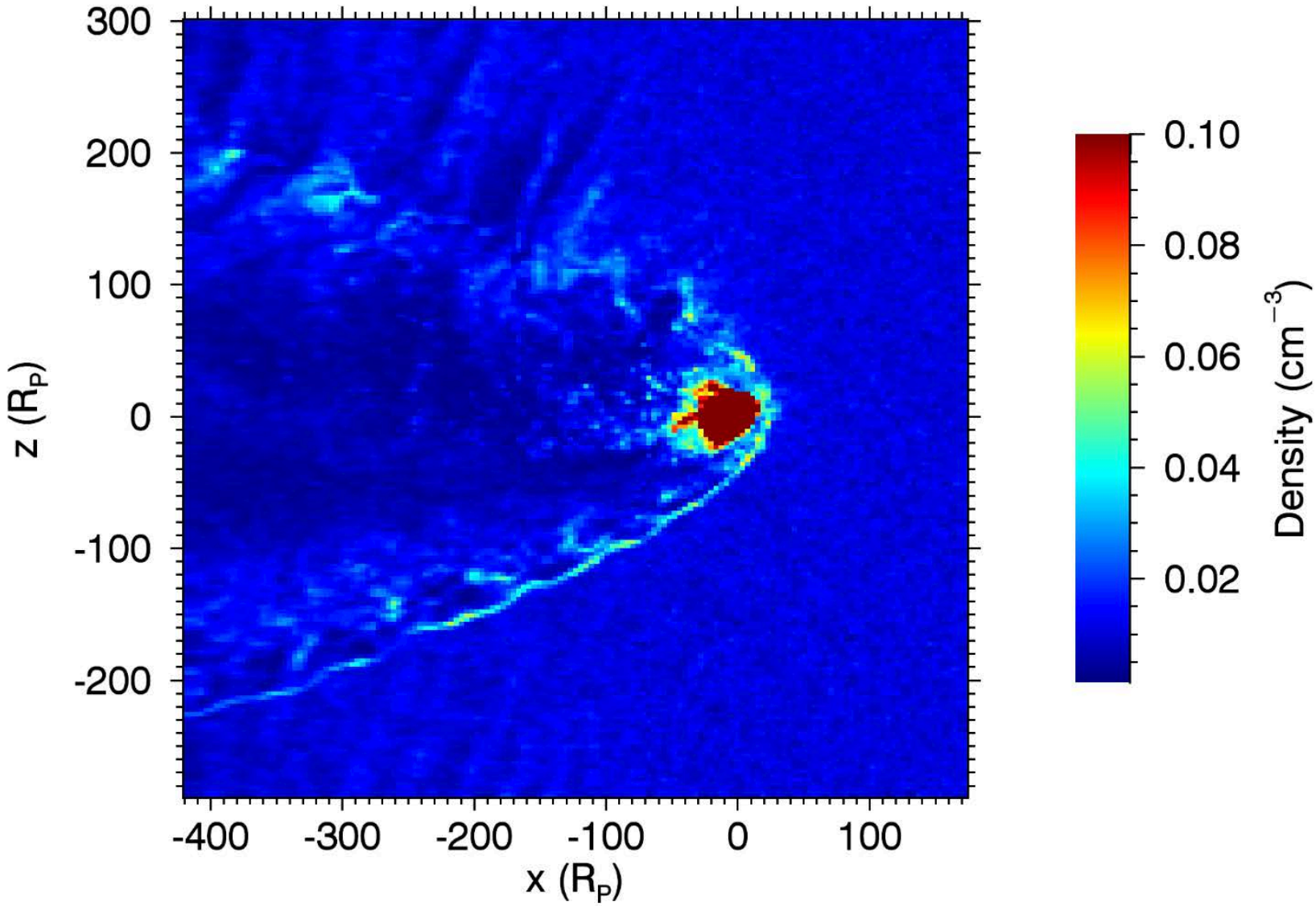
$$n_{sw} = 0.01\ \mathrm{cm}^{-3}, B = 0.2\ \mathrm{nT}, v_{sw} = 340\ \mathrm{km/s}, f(v) \rightarrow\ \mathrm{H}^{+},\ \mathrm{He}^{++}$$



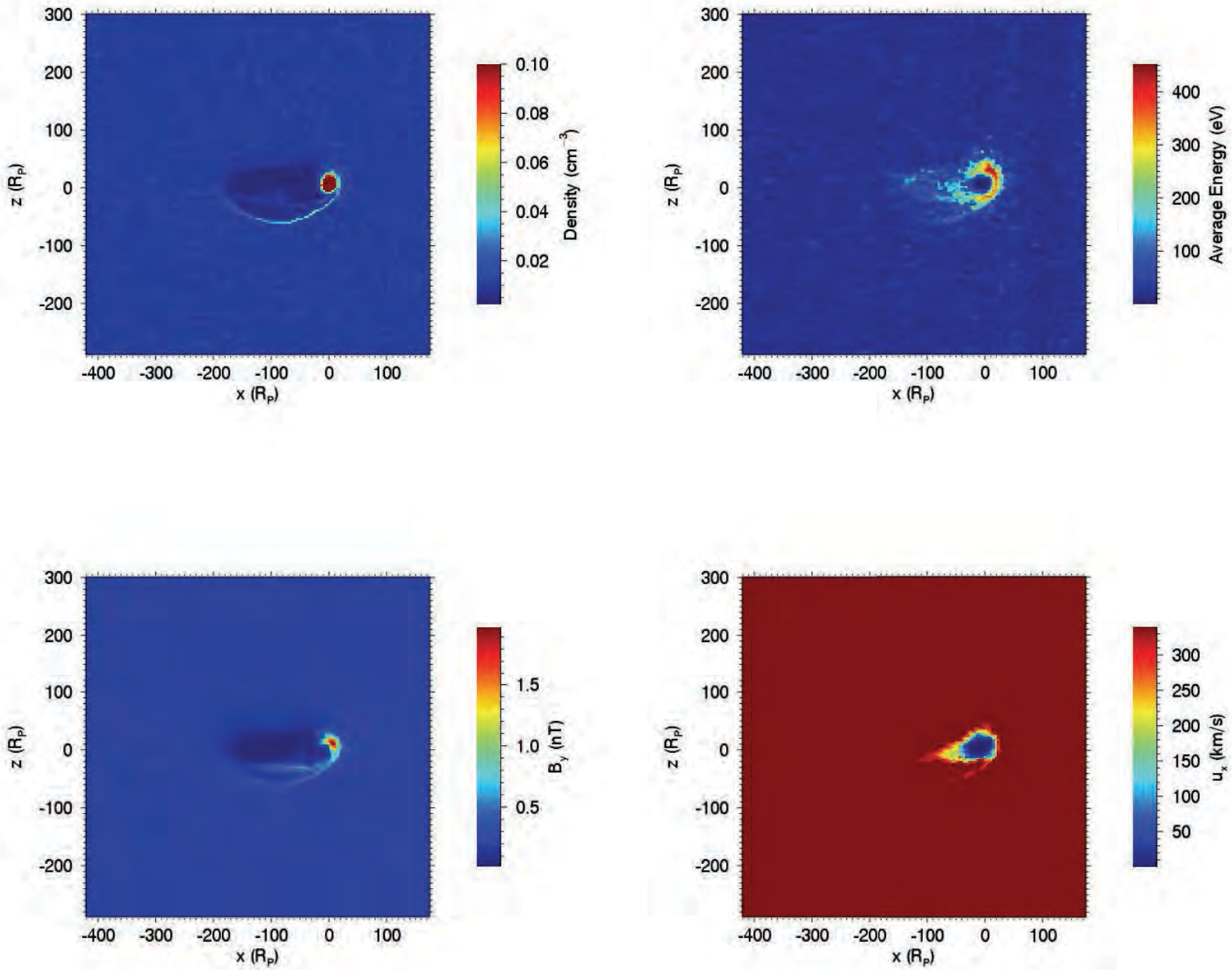
$$n_{sw} = 0.01\ \mathrm{cm}^{-3}, B = 0.2\ \mathrm{nT}, v_{sw} = 340\ \mathrm{km/s}, f(v) \rightarrow\ \mathrm{H}^{+},\ \mathrm{He}^{++}$$



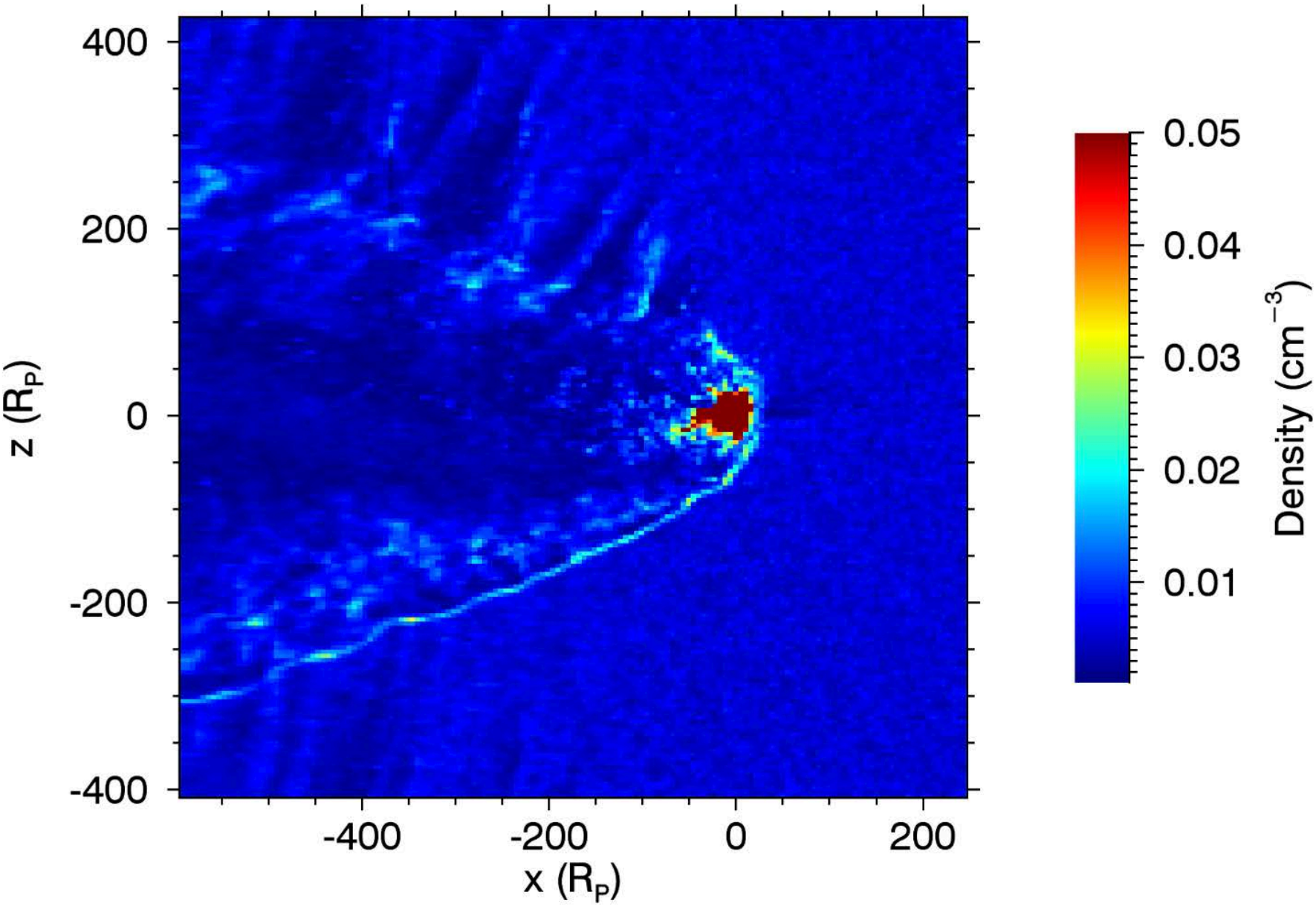
$n_{sw} = 0.01\ \mathrm{cm}^{-3}, B = 0.2\ \mathrm{nT}, v_{sw} = 450\ \mathrm{km/s}, f(v) \rightarrow\ \mathrm{H}^{+},\ \mathrm{He}^{++}, \mathrm{PU}$



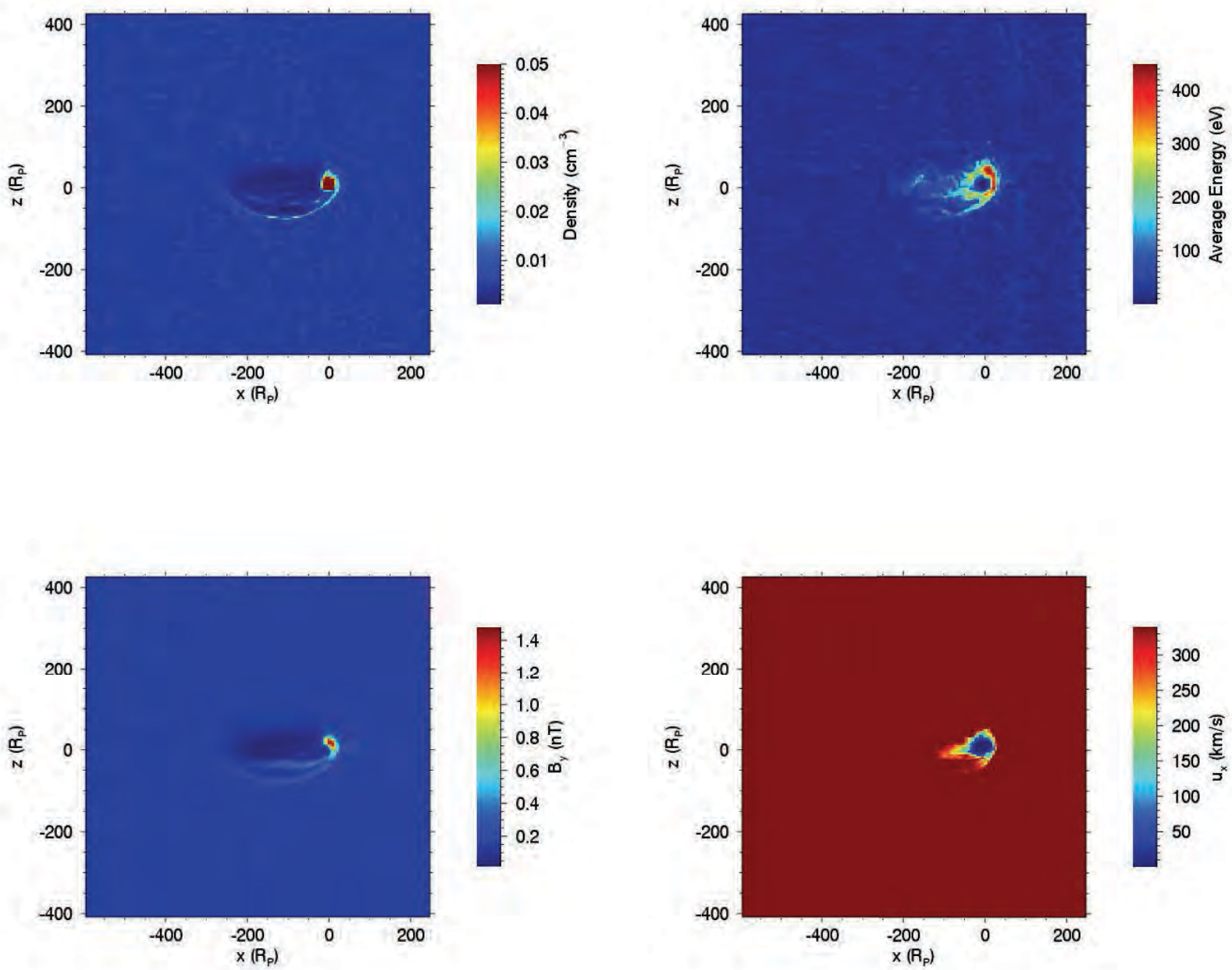
$$n_{sw} = 0.01\ \mathrm{cm}^{-3}, B = 0.2\ \mathrm{nT}, v_{sw} = 450\ \mathrm{km/s}, f(v) \rightarrow\ \mathrm{H}^{+},\ \mathrm{He}^{++}, \mathrm{PU}$$



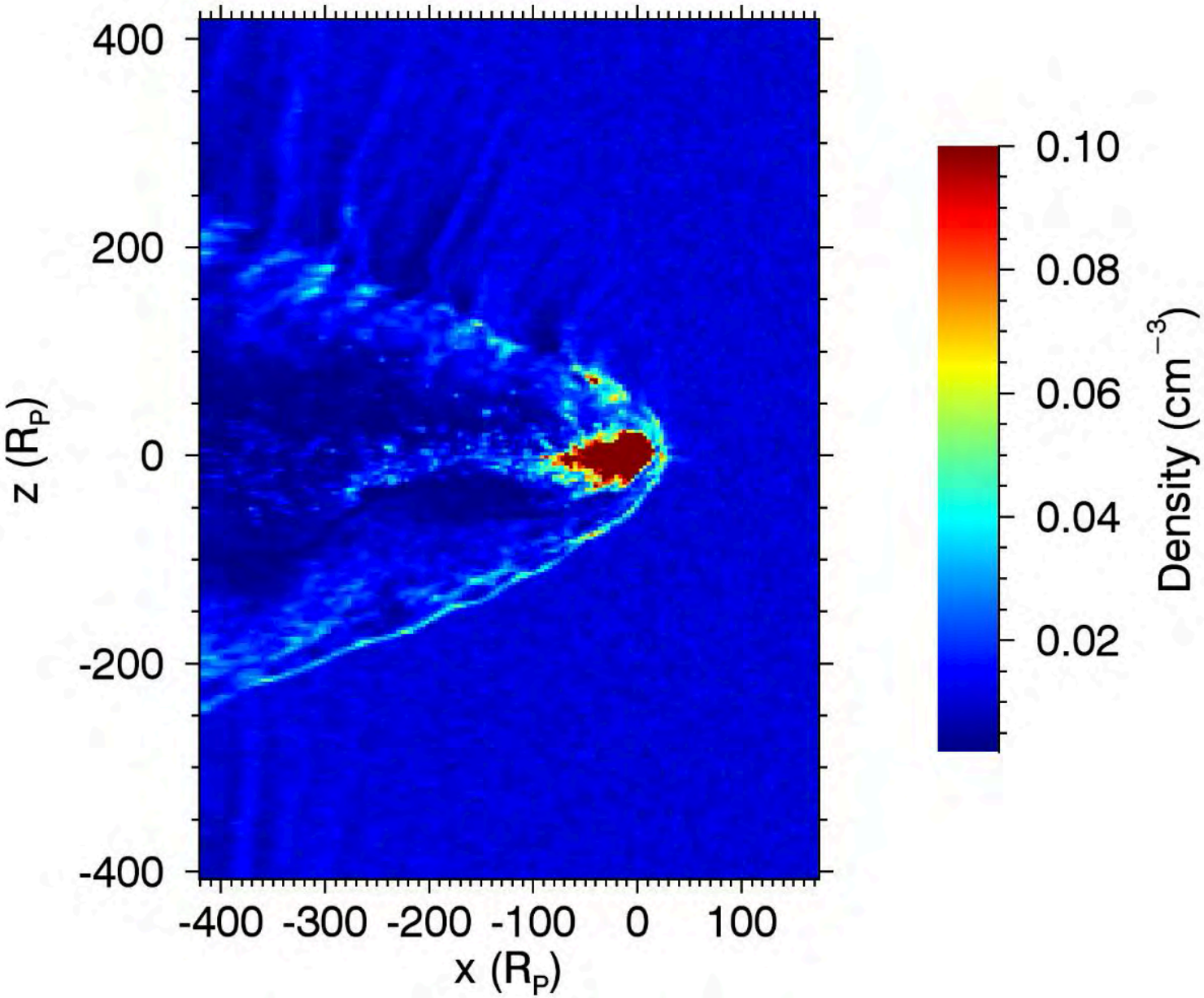
$n_{sw} = 0.005\ \mathrm{cm}^{-3}, B = 0.15\ \mathrm{nT}, v_{sw} = 450\ \mathrm{km/s}, f(v) \rightarrow\ \mathrm{H}^{+},\ \mathrm{He}^{++}, \mathrm{PU}$



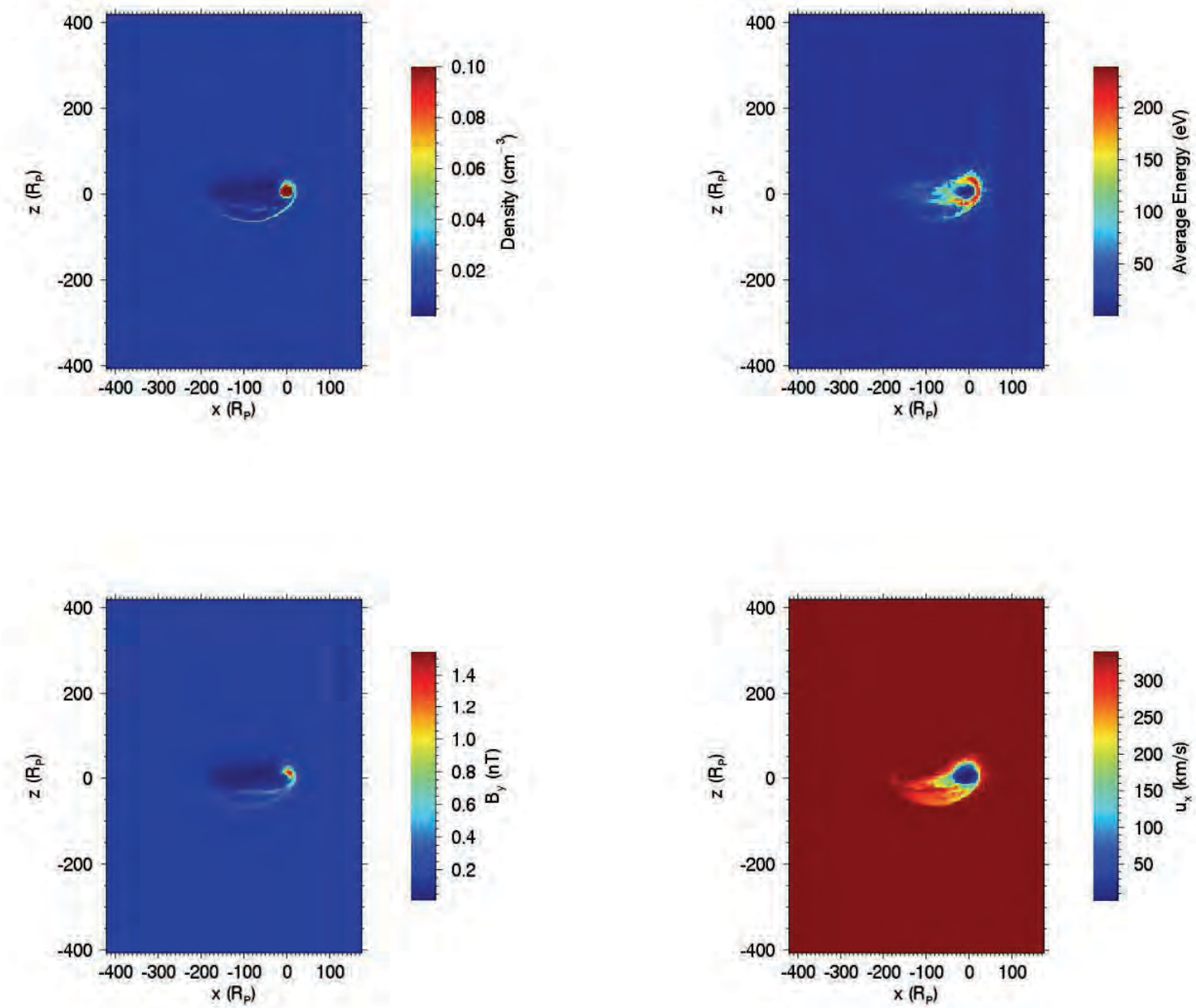
$$n_{sw} = 0.005\ \mathrm{cm}^{-3}, B = 0.15\ \mathrm{nT}, v_{sw} = 450\ \mathrm{km/s}, f(v) \rightarrow\ \mathrm{H}^{+},\ \mathrm{He}^{++}, \mathrm{PU}$$

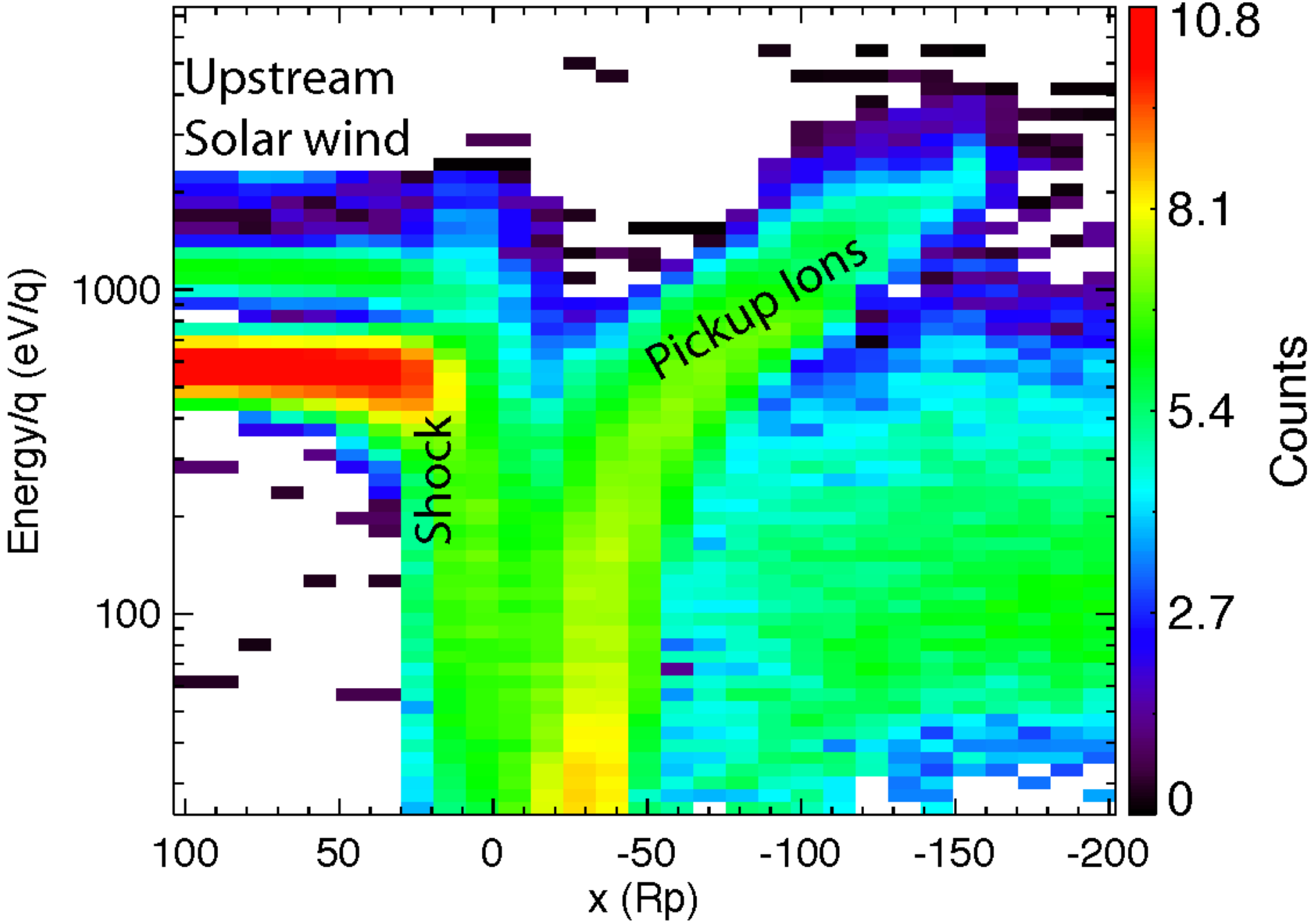


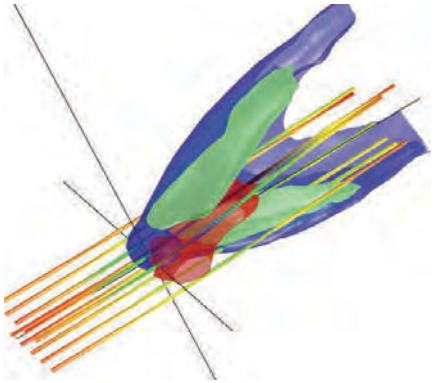
$n_{sw} = 0.01\ \mathrm{cm}^{-3}, B = 0.15\ \mathrm{nT}, v_{sw} = 340\ \mathrm{km/s}, f(v) \rightarrow\ \mathrm{H}^{+},\ \mathrm{He}^{++}, \mathrm{PU}$



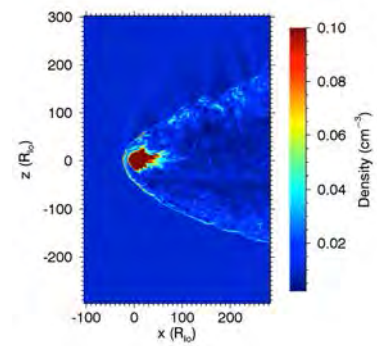
$$n_{sw} = 0.01\ \mathrm{cm}^{-3}, B = 0.15\ \mathrm{nT}, v_{sw} = 340\ \mathrm{km/s}, f(v) \rightarrow\ \mathrm{H}^{+},\ \mathrm{He}^{++}, \mathrm{PU}$$




Upstream
Solar wind
Shock
Pickup Ions
Energy/q (eV/q)
1000
100
100
50
0
-50
-100
-150
-200
x (Rp)
10.8
8.1
5.4
2.7
0
Counts



Conclusions



- Shock structures: Mach cones, weak (attached shocks), full bow shocks depending on neutral escape rate
  - Excellent diagnostic of Pluto's inflated atmosphere
- Significant asymmetry
- Lots of interesting plasma physics
  - Bi-ion waves (hybrid frequency)
  - Kelvin-Helmholtz instability
- Very slow momentum transfer ⇒perturbed flow ~AU??? Long tail!