Plasma environment of the Jupiter moon Io

Ondřej Šebek

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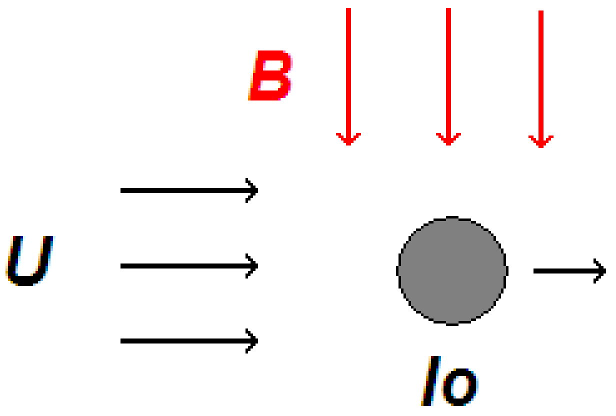
Io

Io, the innermost of the Galilean moons, lies deeply in the Jupiter's magnetosphere. It has strongest volcanic activity in the Solar System. The neutrals eructed from the volcanoes form Io's atmosphere comoposed mainly of SO_2. The neutrals can be ionized and picked up by the flowing plasma of Io's plasma torus which overflows Io with relative velocity 57 km.s^{-1}. To maintain the torus the ionization rate has to be about 10^{28} s^{-1}. Dominant ionization processes are electron impact, photoionization and charge exchange.



Instabilities driven by $T_{\parallel s} < T_{\perp s}$

Pick up process increases temperature anisotropy $A = T_\perp / T_\parallel$ which can generate instabilities, ion cycloron and mirror waves. Both mirror and ion cyclotron waves were observed at Io during *Galileo*'s close flybyes.

Ion cyclotron instability

- LH circular polarization
- cyclotron resonance

Mirror instability

- linear polarization $\delta\mathbf{B} \cdot \mathbf{B}_0 \neq 0$
- Landau resonance

Mirror instability

- Slow and long perturbances of magnetic field ⇒ conservation of magnetic moment $\mu = \frac{mv_\perp^2}{2B}$ = const.
- Bi-Maxwellian unperturbed distribution function:

$$f_0 = n_0 \frac{1}{\pi v_{t\perp}^2} \exp\left(-\frac{v_\perp^2}{v_{t\perp}^2}\right) \frac{1}{\sqrt{\pi} v_{t\parallel}} \exp\left(-\frac{v_\parallel^2}{v_{t\parallel}^2}\right) = n_0 f_\perp f_\parallel .$$

- Perturbance of distribution function:

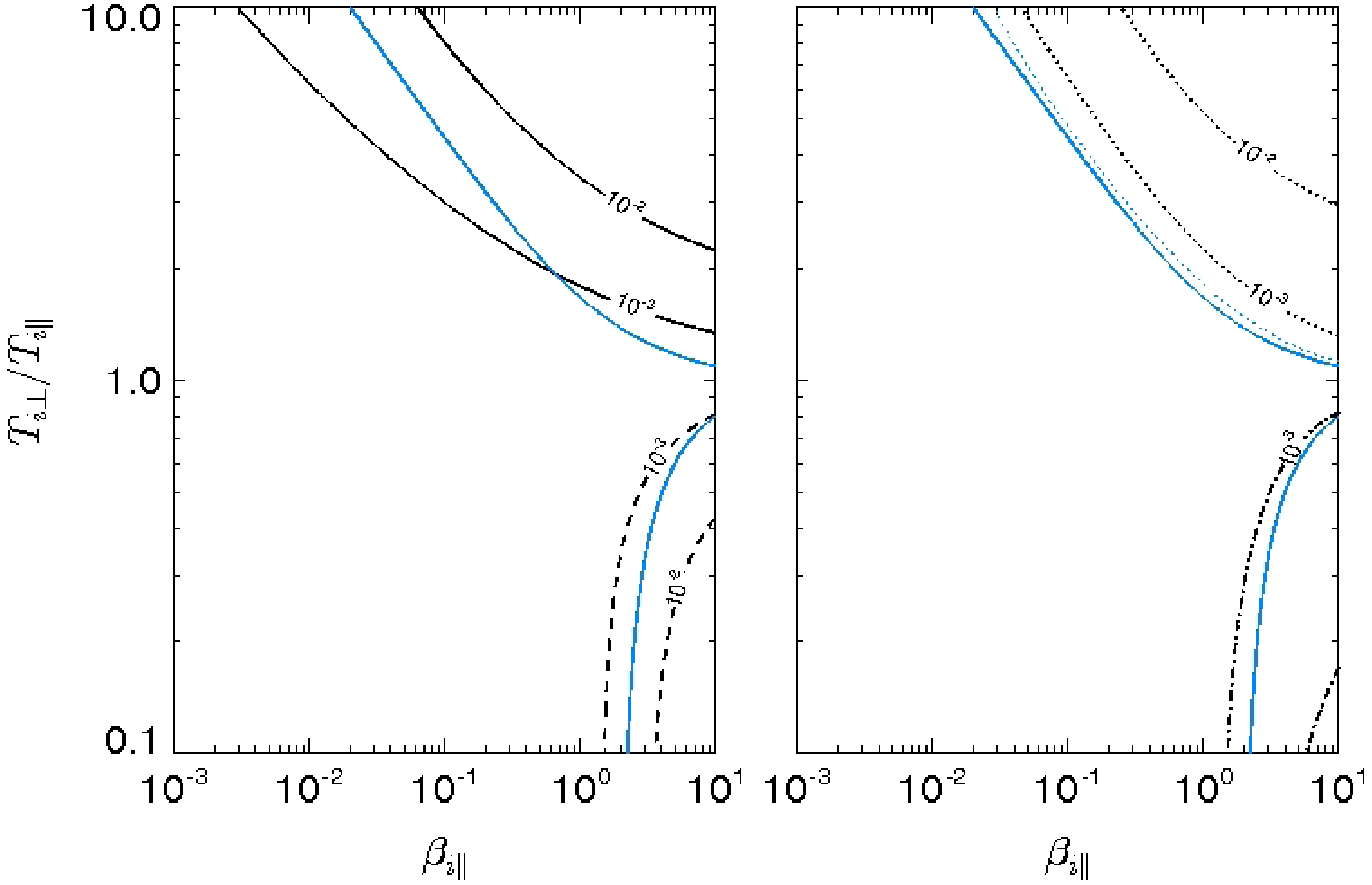
$$\delta f = -\frac{\partial f_0}{\partial v_\parallel}\delta v_\parallel - \frac{\partial f_0}{\partial v_\perp}\delta v_\perp = \frac{1}{v_{t\parallel}^2} f_0 \delta(v_\parallel^2) + \frac{1}{v_{t\perp}^2} f_0 \delta(v_\perp^2) = \left(\frac{1}{v_{t\perp}^2} - \frac{1}{v_{t\parallel}^2}\right) \frac{\delta B}{B} v_\perp^2 f_0 .$$

- Perturbances of pressures:

$$\delta p_\perp = \frac{m}{2} \int v_\perp^2 \delta f dv_x dv_y dv_z = 2p_\perp \left(1 - \frac{T_\perp}{T_\parallel}\right) \frac{\delta B}{B},$$

$$\delta p_\parallel = m \int v_\parallel^2 \delta f dv_x dv_y dv_z = p_\parallel \left(1 - \frac{T_\perp}{T_\parallel}\right) \frac{\delta B}{B}.$$

Linear analysis (AMU=22)



Thresholds of different instabilities driven by the temperature anisotropy $T_{\perp i}/T_{\parallel i}$: ion cyclotron and parallel fire-hose (left), mirror and oblique fire-hose (right). Blue lines denote fluid theory thresholds.

Jovian plasma parameters at Io

PARAMETER	**VALUE**
B_0 (nT), jovian magnetic field	1,720
n_e (electrons cm^{-3}), Eq. av. (range) electron density	2,500 (1,200-3,800)
$\langle$Z$\rangle$: Eq. av. (lobe) ion charge	1.3 (1.3)
$\langle$A$\rangle$: Eq. av. (lobe) ion mass in m_p	22 (19)
n_i (ions cm^{-3}): av. (range) ion no. density	1,920 (960 - 2,900)
$k_B T_i$ (eV): equator (range) ion temperature	70 (20 - 90)
$k_B T_e$ (eV): equator electron temperature	6
v_{cr} (km/s): local corotation velocity	74
v_{Io} (km/s): Io's orbital velocity	17
u (km/s): relative velocity (range).	57 (53 - 57)
v_A (km/s): Eq. (range) Alfvén speed	180 (150 - 340)
c_s (km/s): Eq. (range) sound speed	29 (27 - 53)
$B_0^2/2\mu_0$ (nPa): Eq. (lobe) magnetic pressure	1,200 (1,700)

[*Kivelson et al.*, 2004]

Simulation model

Current advance method and cyclic leapfrog scheme (A. Matthews, 1994):

- particle in cell scheme,
- kinetic ions represented by macro particles,
- fluid isotropic electrons with constant temperature.

Equation set:

- Faraday's law: $\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$,
- Ohm's law: $\mathbf{E} = \frac{1}{\rho_c}\left(\frac{(\nabla\times\mathbf{B})\times\mathbf{B}}{\mu_0} - \mathbf{J}_i \times \mathbf{B} - \nabla p_e\right) + \eta\,(\nabla \times \mathbf{B})$,
- Newton's law: $\frac{d\mathbf{v}_s}{dt} = \frac{q_s}{m_s}\,(\mathbf{E} + \mathbf{v}_s \times \mathbf{B})$,
- ion position: $\frac{d\mathbf{x}_s}{dt} = \mathbf{v}_s$.
- + ionic current density evolution: $\frac{d\mathbf{J}_i}{dt} = \sum_s \frac{q_s}{m_s}\,(\rho_{c,s}\mathbf{E} + \mathbf{J}_s \times \mathbf{B})$.

Charge exchange

Ions may exchange charge with neutrals. The probability that a given macro-particle can exchange its charge with a neutral during a given time step (with duration Δt) is

$$p \propto -n_{\mathrm{neutral}}\, v_{\mathrm{rel}}\, \sigma_{\mathrm{exch}}\, \Delta t$$

where

v_{rel}	Relative velocity between the ion and neutral. We assume that neutrals are at rest in Io's rest frame ($\boldsymbol{v}_{\mathrm{neutral}} = 0$).
σ_{exch}	Cross-section of the charge exchange process. Normally $\sigma_{\mathrm{exch}} = f(v_{\mathrm{rel}})$, we assume $\sigma_{\mathrm{exch}} = 1.5 \cdot 10^{-15}\ \mathrm{cm}^{-2}$ (a constant).

Photo-ionization

Ions produced by photoionization and electron impact ionization are injected in the vicinity of Io within $R = 5.6\,R_{\mathrm{Io}}$. Each new ion is injected with random polar angle φ and radial distance r from Io given as

$$r = R^{\alpha}\,R_{\mathrm{Io}}^{1-\alpha},$$

where α is random number with normal distribution between 0 and 1. In this model we assume, that newborn ions have zero bulk and thermal temperatures and AMU = 22 as the torus ions.

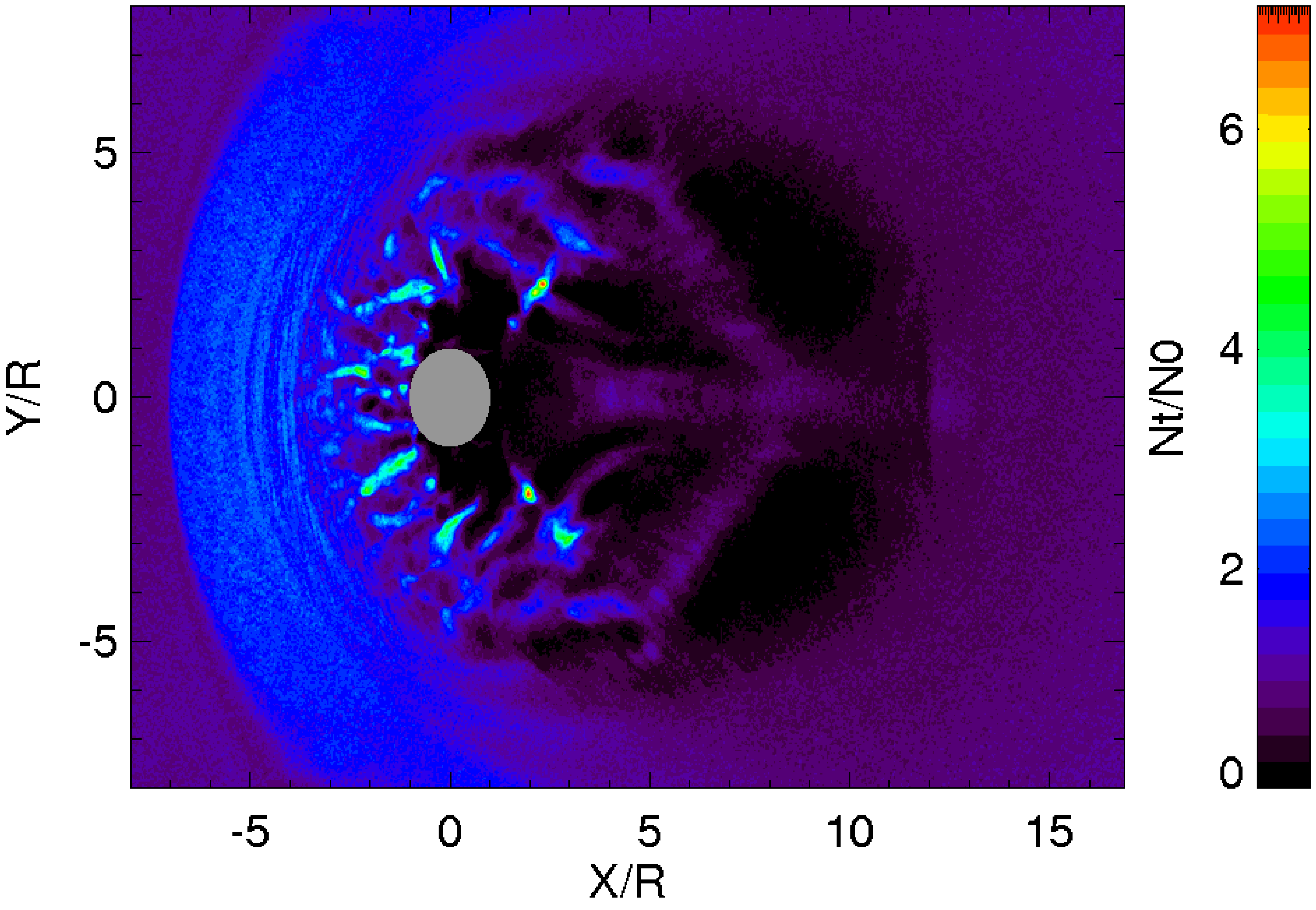
Boundary conditions

- For simplicity we assume periodic boundary conditions at the borders of the simulation box.
- Electric field is set to zero in the interior of Io.
- Density of ions is kept above a minimum value to ensure that the electric field does not diverge ($n_{\mathrm{min}} = 0.05\, n_{i,\mathrm{flow}}$).
- Bulk speed of plasma is set to zero in the interior of Io.
- Charged particles which hit the surface of Io are removed from the simulation.

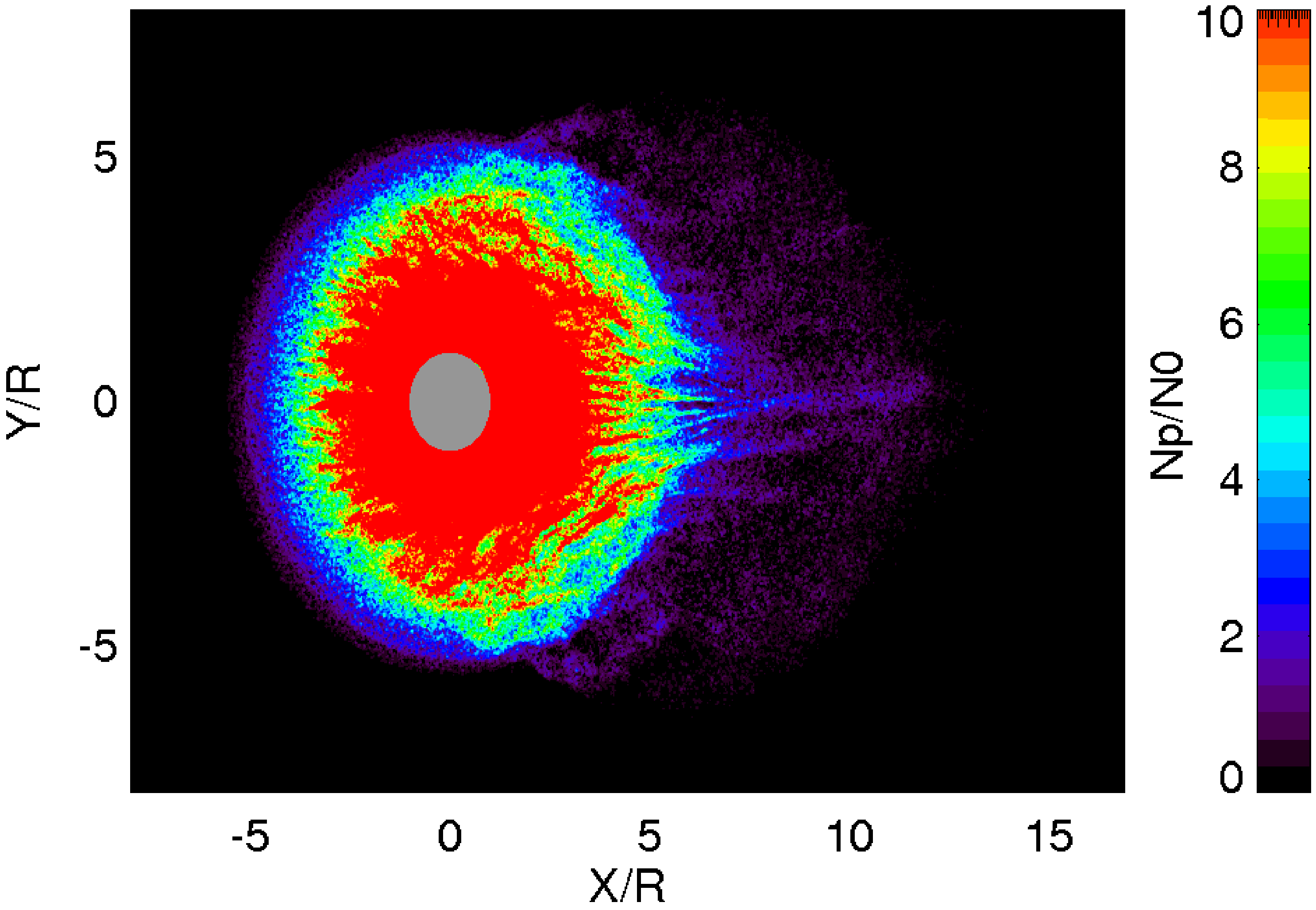
Simulation setup

PARAMETER	**VALUE**
Spatial resolution $\Delta x = \Delta y$	$0.2\ c/\omega_{pi,\mathrm{flow}}$
Temporal resolution (time step) Δt	$0.02\ \omega_{gi,\mathrm{flow}}^{-1}$
Spatial size of the system L_x/L_y	1,300/1,000 cells $= 26/20\ R_{\mathrm{Io}}$
Total simulation time	$300\ \omega_{gi,\mathrm{flow}}^{-1}$
$\beta_{i,\mathrm{flow}}$ / $\beta_{e,\mathrm{flow}}$	0.05 / 0.0022
Number of macro-particles per cell	20
Flow velocity v_{flow}	$0.3\ v_{A,\mathrm{flow}}$
Magnetic field in (X,Y) plane	$\boldsymbol{B} = (0,1,0)$

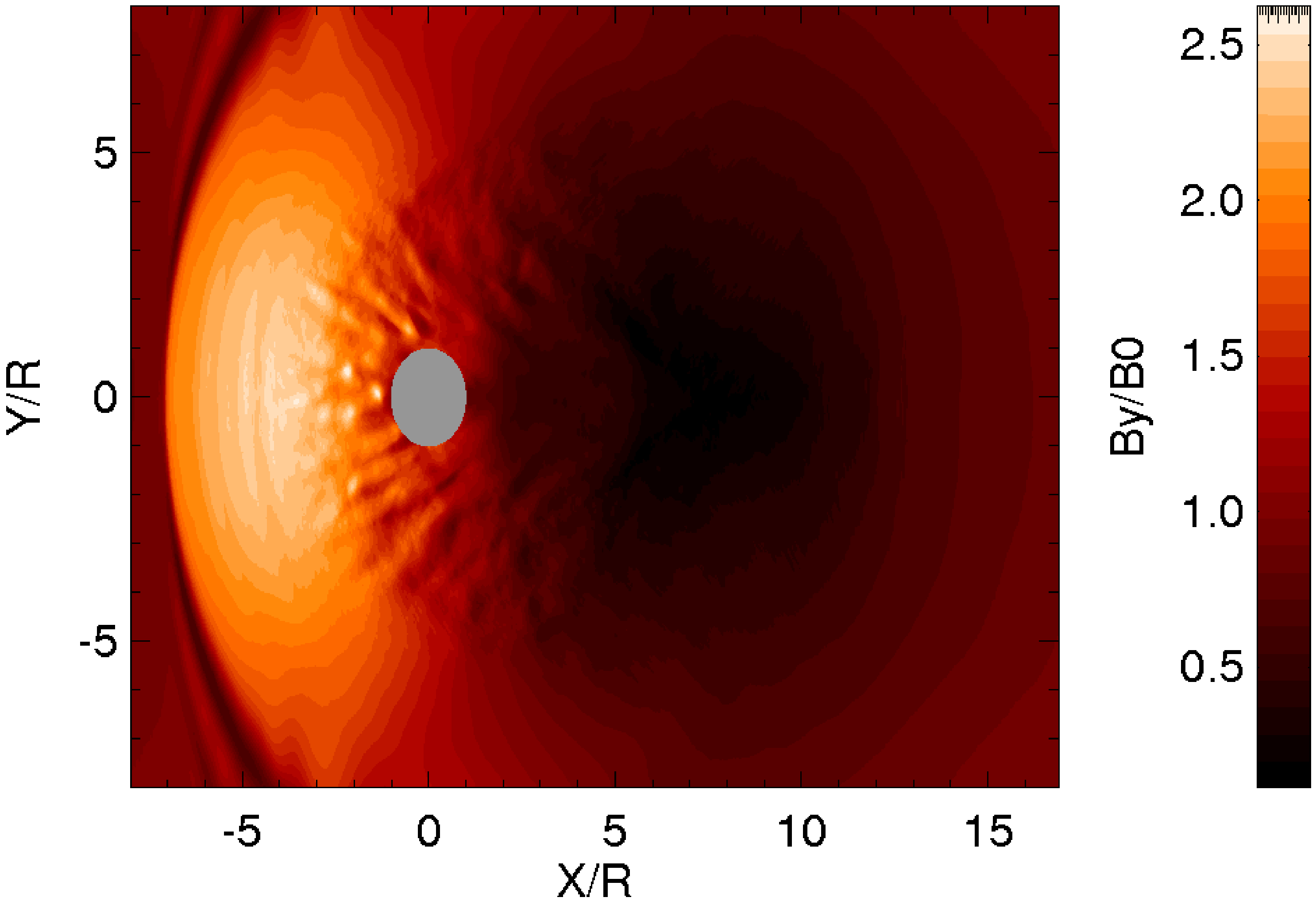
Torus plasma density $n_t/n_{0,\text{flow}}$



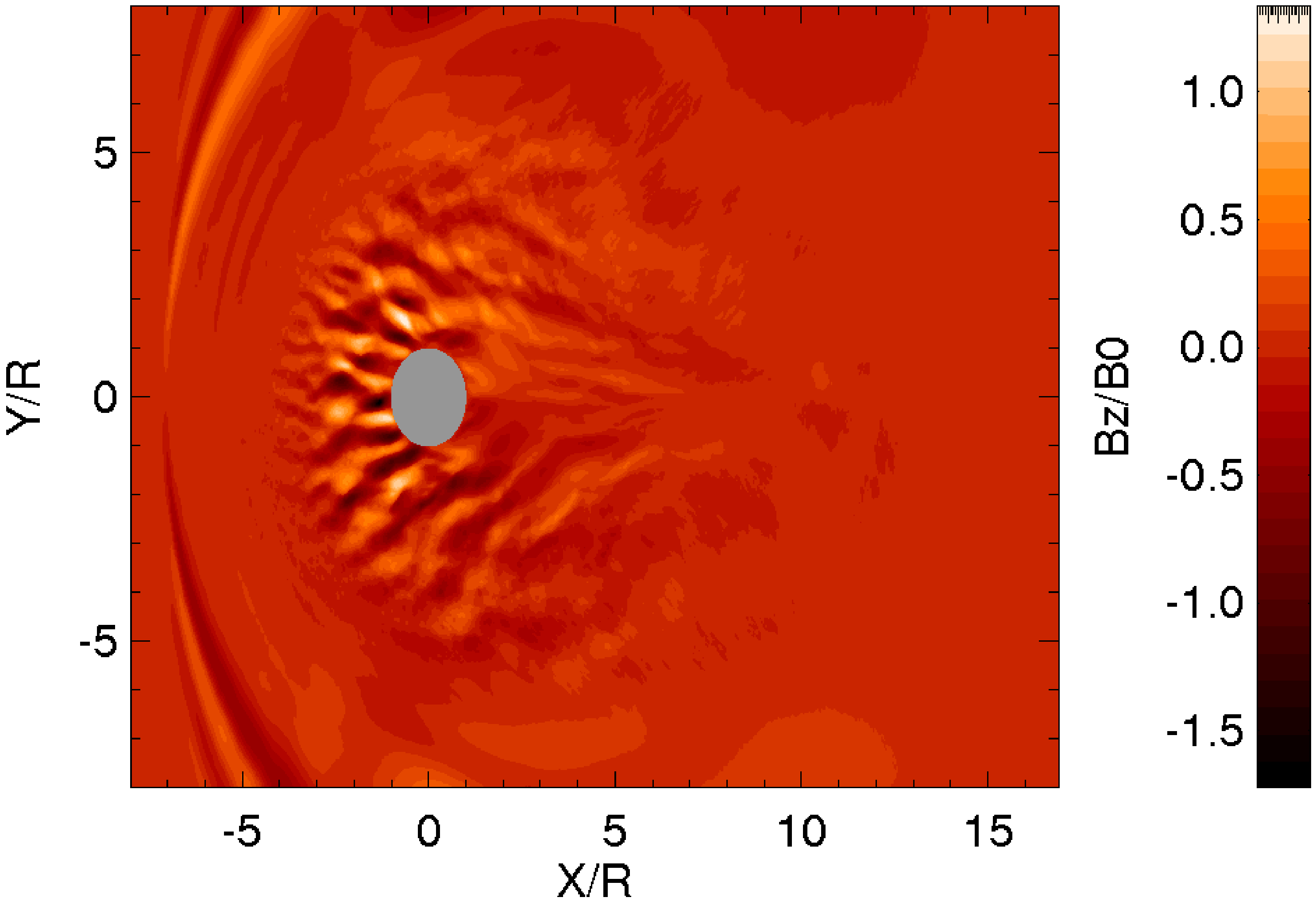
Pickup plasma density $n_p/n_{0,\mathrm{flow}}$



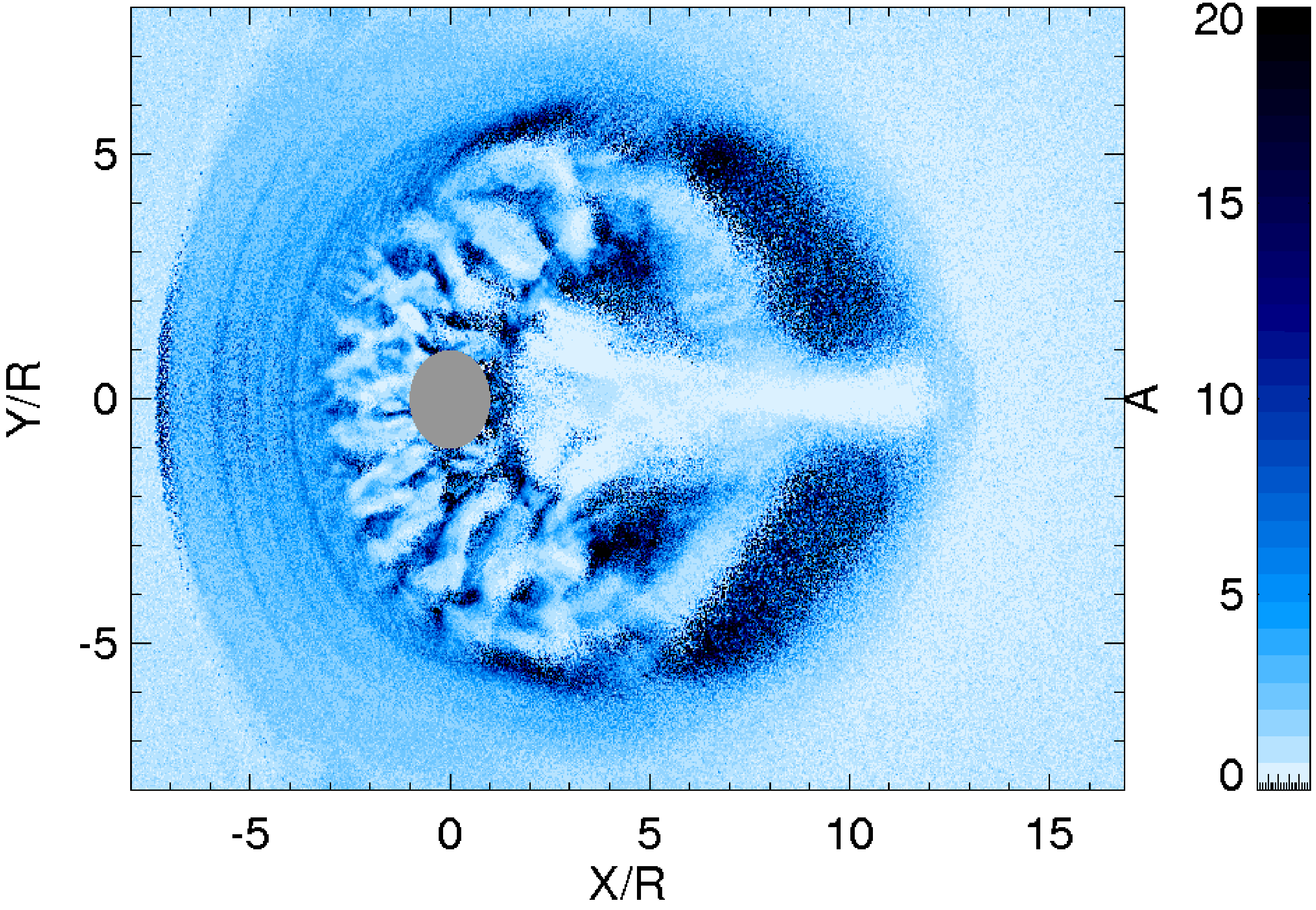
Magnetic field component $B_y/B_{0,\text{flow}}$



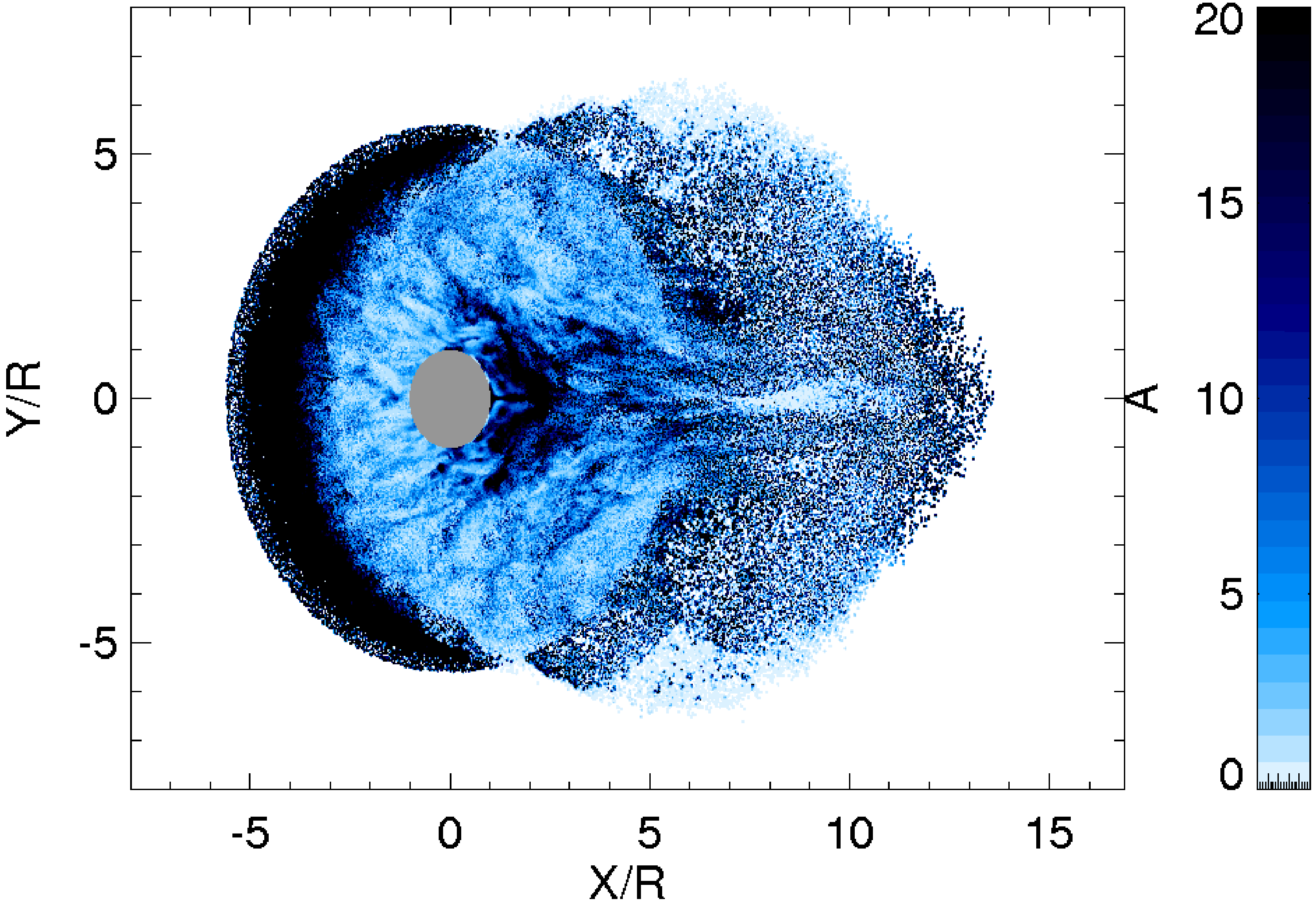
Magnetic field component $B_z/B_{0,\text{flow}}$



Temperature anisotropy $A_t = T_{\perp,t}/T_{\parallel,t}$ of the torus plasma



Temperature anisotropy $A_p = T_{\perp,p}/T_{\parallel,p}$ of the picked up plasma



Conclusions

- Charge exchange, electron impact ionization and photoionization processes at Io produce dense immobile (in Io's rest frame) plasma, which represent an efficient obstacle to the magnetised corrotating Jovian plasma.
- Our simulation results confirm that initially immobile ions are picked-up by the plasma flow forming velocity distribution functions mostly with a ring-VDF shape, which have naturally $T_{i\perp} > T_{i\|}$.
- Temperature anisotropy $A = T_{\perp}/T_{\|}$ of the pickup ions is sufficiently high to generate both ion cyclotron and mirror waves.