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# Jovian plasma torus interaction with Europa: 3D hybrid kinetic simulation. First results

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## ABSTRACT

The hybrid kinetic model supports comprehensive simulation of the interaction between different spatial and energetic elements of the Europa moon-magnetosphere system with respect to variable upstream magnetic field and flux or density distributions of plasma and energetic ions, electrons, and neutral atoms. This capability is critical for improving the interpretation of the existing Europa flyby measurements from the Galileo orbiter mission, and for planning flyby and orbital measurements (including the surface and atmospheric compositions) for future missions. The simulations are based on recent models of the atmosphere of Europa (Cassidy et al., 2007; Shematovich et al., 2005). In contrast to previous approaches with MHD simulations, the hybrid model allows us to fully take into account the finite gyroradius effect and electron pressure, and to correctly estimate the ion velocity distribution and the fluxes along the magnetic field (assuming an initial Maxwellian velocity distribution for upstream background ions). Non-thermal distributions of upstream plasma will be addressed in future work. Photoionization, electron-impact ionization, charge exchange and collisions between the ions and neutrals are also included in our model. We consider two models for background plasma: (a) with O<sup>+</sup> ions; (b) with O<sup>+</sup> and S<sup>+</sup> ions. The majority of O<sub>2</sub> atmosphere is thermal with an extended cold population (Cassidy et al., 2007). A few first simulations already include an induced magnetic dipole; however, several important effects of induced magnetic fields arising from oceanic shell conductivity will be addressed in later work.

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## 1. Introduction

The interaction of the Jovian plasma torus with Europa and other moons is a fundamental problem in magnetospheric physics (see, e.g., Goertz, 1980; Southwood et al., 1980; Southwood and Dunlop, 1984; Wolf-Gladrow et al., 1987; Ip, 1990; Schreier et al., 1993; Lellouch, 1996). The plasma environment near Europa was studied by flyby observations during the Galileo prime mission and the extended Galileo Europa mission (Kivelson et al., 1997; Khurana et al., 1998; Kivelson et al., 1999; Paterson et al., 1999).

Europa, one of the icy moons of Jupiter, was encountered by the Galileo satellite three times during its primary mission, seven times during its Galileo Europa Mission (GEM), and once during Galileo Millennium Mission (GMM). Europa is located at a radial distance of 9.4  $R_J$  (Jovian radii, 71,492 km) from Jupiter, and has a radius of 1560 km (1  $R_E$ ).

The interaction of Europa with the magnetized plasma of the Jovian plasma sheet gives rise to so-called Alfvén wing, which have been extensively studied in the case of Io (e.g., Neubauer, 1980; Southwood et al., 1980; Herbert, 1985; Lipatov and Combi, 2006). Neubauer (1998, 1999) has shown theoretically how an Alfvén wing is modified by an induced magnetic field, such as that found at Europa (Kivelson et al., 2000). Observations by Kivelson et al. (1992) show the generation of the ultra-low frequency electromagnetic waves in Europa's wake. These waves have frequencies near and below the gyrofrequencies of the ion species in the plasma torus (e.g., ionized sulfur, oxygen, and protons). Ion cyclotron waves grow when ion distribution functions are sufficiently anisotropic, as occurs when ion pickup creates a ring distribution of ions (in velocity space). The analysis of these waves was done by Volwerk et al. (2001).

The most general and accurate theoretical approach for this problem would require the solution of a nonlinear coupled set of integro-MHD/kinetic-Boltzmann equations which describe the dynamics of Jupiter's corotating magnetospheric plasma, pickup ions, and ionosphere, together with the neutrals from Europa's atmosphere. To first order, the plasma and neutral atoms and

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molecules are coupled by charge exchange and ionization. The characteristic scale of the ionized components is usually determined by the typical ion gyroradius, which for Europa is much less than characteristic global magnetospheric scales of interest, but which may be comparable to the vertical thickness of the magnetospheric current sheet near Europa. Kinetic approaches, such as direct simulation Monte Carlo, have been applied to understand global aspects of the neutral atmosphere (Marconi et al., 1996; Austin and Goldstein, 2000). Plasma kinetic simulations are, however, much more complicated, and even at the current stage of computational technology require some approximations and compromises to make some initial progress. Several approaches have been formulated for including the neutral component and pickup ions self-consistently in models that describe the interaction of the plasma torus with Europa.

There have been recent efforts to improve and extend the pre-Galileo simulations for Europa, Io and Ganymede, both in terms of the MHD (Kabin et al., 1999; Combi et al., 1998; Linker et al., 1998; Kabin et al., 2001; Jia et al., 2008) and the electrodynamic (Saur et al., 1998, 1999; Schilling et al., 2008) approaches. These two approaches are distinguished by the physical assumptions that they include. MHD models cannot, at least yet, include the effects of realistic conductivities (Hall and Pedersen) or charge separation effects which are likely to be an important very close to moon where the neutral densities are large and the electric potential can introduce non-symmetric flow around the body. MHD models for Io either include constant artificial conductivity (Linker et al., 1998) or assume perfect conductivity (Combi et al., 1998). Comparisons of the sets of published results do not indicate that this choice has any important consequence. The MHD model of Europa developed by Kabin et al. (1999) includes an exospheric mass loading, ion-neutral charge exchange, and recombination. Further development of this model by Liu et al. (2000) already includes a possible intrinsic dipole magnetic field of Europa.

Galileo flyby measurements E4, E6 (plasma only), E11, E12, E14, E15, E19, and E26 demonstrate several features in the plasma environment: Alfvén wing formation and an induced magnetosphere, possible existence of the dipole-type induced magnetic field, and variation of the magnetic field in the plasma wake due to diamagnetic currents. The measurements also demonstrate mass loading of the plasma torus plasma by pickup ions and the interaction of the ions with the surface of Europa. For an interpretation of these data we need to use a kinetic model because of effects of the finite ion gyroradius.

Hybrid models have been shown to be very useful in studying the complex plasma wave processes of space, astrophysical, and laboratory plasmas. These models provide a kinetic description of plasmas in local regions, together with the possibility of performing global simulations of the whole plasma system. Revolutionary advances in computational speed and memory are making hybrid simulations of various space plasma problems a much more effective general tool.

In this paper, we apply a time-dependent Boltzmann equation (a “particle in cell” approach) together with a hybrid kinetic plasma (ion kinetic) model in three spatial dimensions (see, e.g., Lipatov and Combi, 2006), using a prescribed but adjustable neutral atmosphere model for Europa. A Boltzmann simulation is applied to model charge exchange between incoming and pickup ions and the immobile atmospheric neutrals. In this paper we discuss the first results of the hybrid kinetic simulation of Europa’s environment—namely, the global plasma structures (formation of the magnetic barrier, Alfvén wing, pickup ion tail, etc.), and the computed map for the ion flux on the surface of the moon. The results of these kinetic simulations are compared with those obtained from related MHD models and the Galileo E4 flyby

observational data. Comparison of the results of our hybrid simulation for other Galileo flybys will be presented in future publications.

The paper is organized as follows: in Section 2 we present the computational model and a formulation of the problem. In Section 3 we present the results of the modeling of the plasma environment near Europa and the comparison with observational data. Finally, in Section 4 we summarize our results and discuss the future development of our computational model.

## 2. Formulation of the problem and mathematical model

### 2.1. Simulation model

To study the interaction of the plasma torus with the ionized and neutral components of Europa’s environment, we use a quasineutral hybrid model for ions and electrons. The model includes ionization (which in the Europa environment is dominated by electron impact ionization, not photoionization) and charge exchange. The atmosphere is considered to be an immobile component in this paper.

In our hybrid simulations, the dynamics of upstream ions and implanted ions are described in a kinetic approach, while the dynamics of the electrons are described in a hydrodynamical approximation. The details of this plasma-neutral approach were developed early for the study of the Io–Jovian plasma interaction (Lipatov and Combi, 2006). Since the Jovian torus plasma may also include higher energy ions, we expect to use a combined code which operates with high-energy ions in a kinetic approximation, while low-energy ions may be considered in a drift-kinetic approximation (see, e.g., Lipatov et al., 2005). This approach allows us to perform a multiscale simulation with different values of the gyroradius of ions. In cases where the charging of the surface of Europa becomes very important, we are planning to incorporate a non-neutral full particle code into the hybrid code in a region near the Europa surface (see, e.g., Hewett and Langdon, 1987; Lipatov and Lobachev, 1996). Our present quasineutral code will be applied for external global region far from Europa.

The neutral atmosphere of Europa serves as a source of new ions, mainly by electron impact ionization from corotating (or nearly corotating) plasma and also by photoionization. The neutral atmospheric molecules also serve as collisional targets for charge exchange by corotating ions. The impacting ions consist of both upstream torus ions and newly implanted ions which are picked up by the motional electric field.

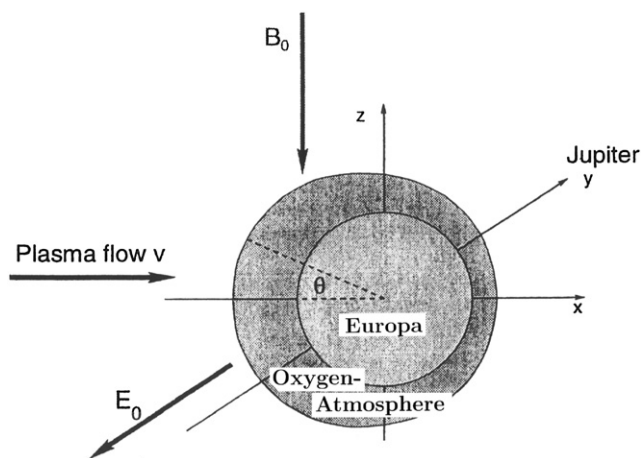


Fig. 1. Europa's environment and the system of coordinates.

Europa is considered as a weakly conducting sphere. The composition of the plasma torus includes a thermal particle distribution with a Maxwellian core together with extremely energetic particles that may be considered either as test particles or may be fully incorporated into the kinetic simulation. In the current simulation we consider only a thermal part of particle distribution with molecular mass/charge of 26 corresponding to  $\text{SO}^{++}$ .

We assume that Europa has a radius  $R_E = 1560$  km. We have also adopted a two-species description for the neutral  $\text{O}_2$  exosphere of exponential form (Cassidy et al., 2007; Shematovich et al., 2005)

$$n_{\text{neutral},k} \approx n_{\text{atmos},k} \exp[-(r-r_{\text{exobase},k})/h_{\text{atmos},k}], \quad (1)$$

where  $n_{\text{atmos},k}$  denotes the maximum value of the neutral density extrapolated to the exobase ( $r_{\text{exobase},\text{cold}} \approx 1700$  km;

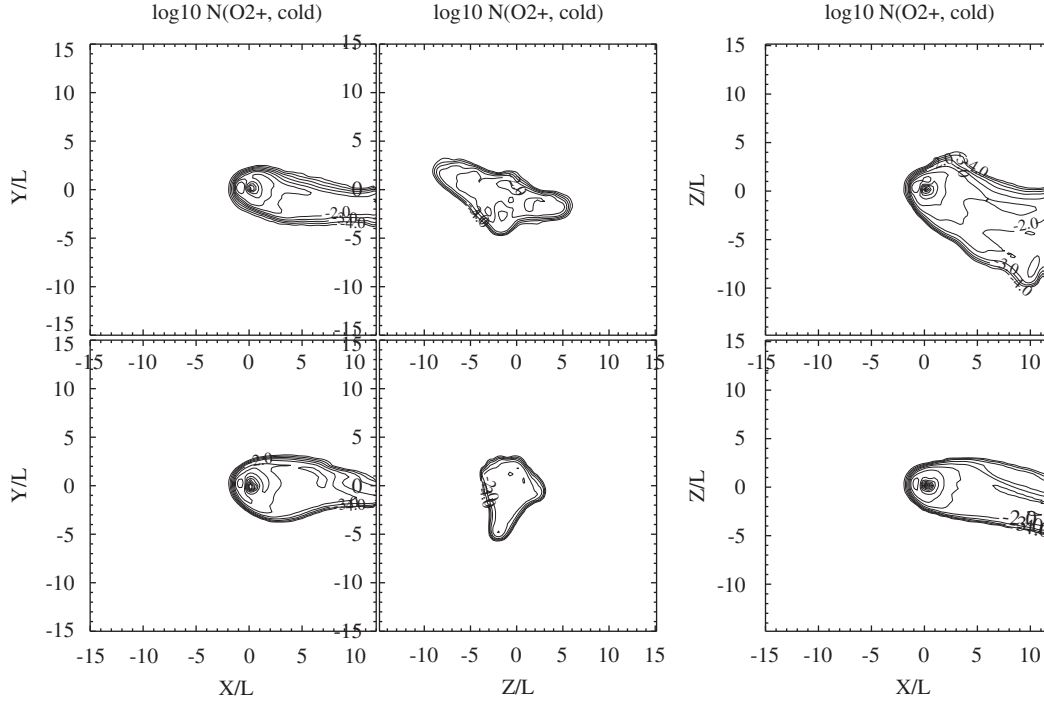


Fig. 2. 2-D cuts of the pickup ion  $\text{O}_2^+$  (cold) density profile: model A (top) and for model B (bottom).

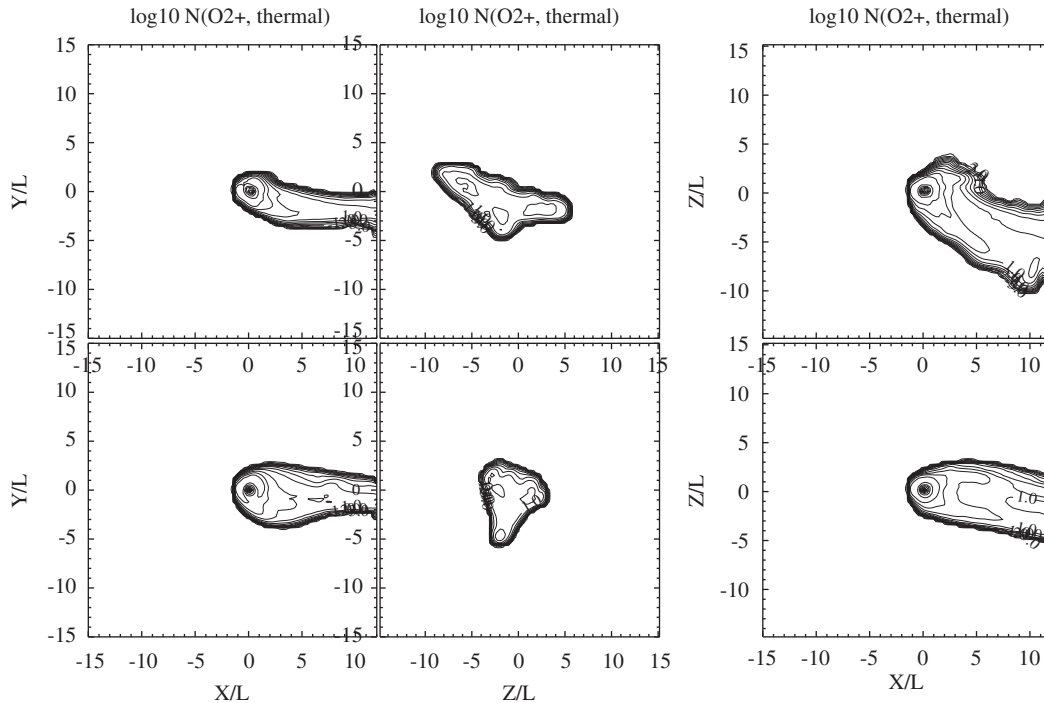


Fig. 3. 2-D cuts of the pickup ion  $\text{O}_2^+$  (thermal) density profile: model A (top) and model B (bottom).

$r_{\text{exobase,thermal}} \approx 1560 \text{ km}$ ), and index  $k$  denotes either cold or thermal. Here  $h_{\text{atmos,O}_2,\text{cold}} = 200 \text{ km}$  and  $h_{\text{atmos,O}_2,\text{thermal}} = 30 \text{ km}$ . We also include an immobile shell-like ionosphere with density profile at  $R_{\text{iono}} = R_E$

$$n_{\text{iono}} \approx n_{\text{iono},R_{\text{iono}}} \exp[-(r-R_{\text{iono}})^2/\delta_{\text{iono}}^2]. \quad (2)$$

The production rate of new ions from the exosphere near Europa corresponds to

$$G_{\text{exo},k} \propto v_{i,k} n_{\text{atmos},k} \exp[-(r-r_{\text{exobase},k})/h_{\text{atmos},k}], \quad (3)$$

where  $n_{\text{atmos},k}$  denotes the value of the neutral component density at  $r=r_{\text{exobase}}$  and  $v_{i,k}$  is the effective ionization rate per atom or

molecule of species  $k$ .  $v_{i,k}$  includes the photoionization  $v_{ph}$ , and the electron impact ionization by the background  $v_{e,im}$  and the secondary  $v_{e^*,im}$  electrons.

Initially, the computational domain contains only supersonic and sub-Alfvénic plasma torus flow with a homogeneous spatial distribution and a Maxwellian velocity distribution; the pickup ions have a weak density and spherical spatial distribution. The magnetic field and electric fields are  $\mathbf{B} = \mathbf{B}_0$  and  $\mathbf{E} = -\mathbf{U}_0 \times \mathbf{B}_0$ . Inside Europa the electromagnetic fields are  $\mathbf{E} = 0$  and  $\mathbf{B} = \mathbf{B}_0$ , and the bulk velocities of ions and electrons are also equal to zero. Here the  $X$ -axis is directed in the corotation direction, the  $Y$ -axis is directed toward Jupiter, and the  $Z$ -axis is directed to the north, as shown in Fig. 1.

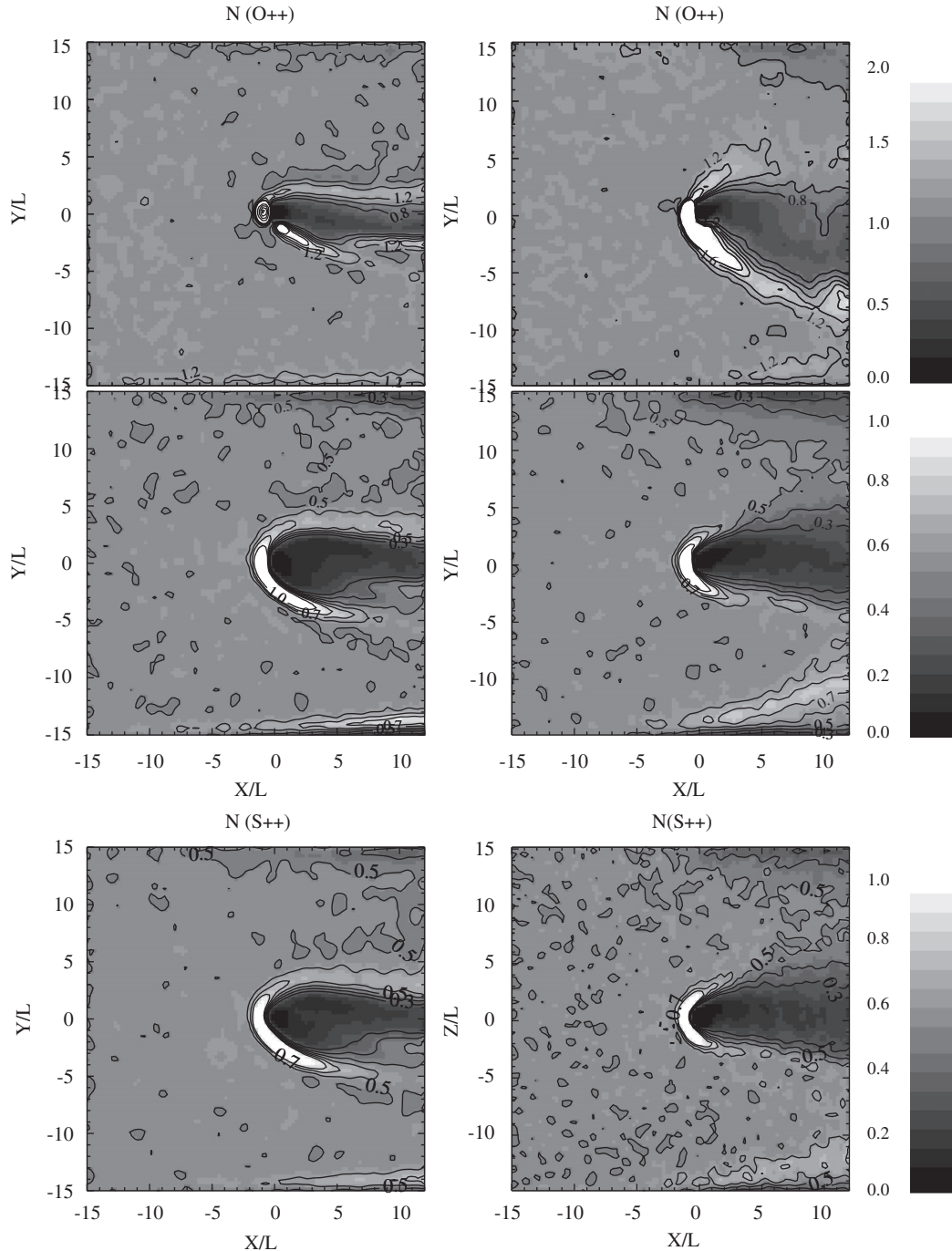


Fig. 4. 2-D cuts of the background  $\text{SO}^+$  density profiles for model A (top) and model B (middle), and  $\text{S}^+$  density profile for Model B (bottom).

At  $t > 0$  we begin to inject the pickup ions with a distribution according to Eqs. (2) and (3). Far upstream ( $z = -DZ/2$ ), the ion flux is assumed to have a Maxwellian distribution.

Far downstream, we adopted a free escape condition for particles and Sommerfeld's radiation condition for the magnetic

field. On the side boundaries ( $y = \pm DY/2$  and  $x = \pm DX/2$ ), periodic boundary conditions were imposed for incoming flow particles and the electromagnetic field. In some cases we also tested the use of the upstream boundary condition for the electromagnetic field on the side boundaries. In these situations we also employed

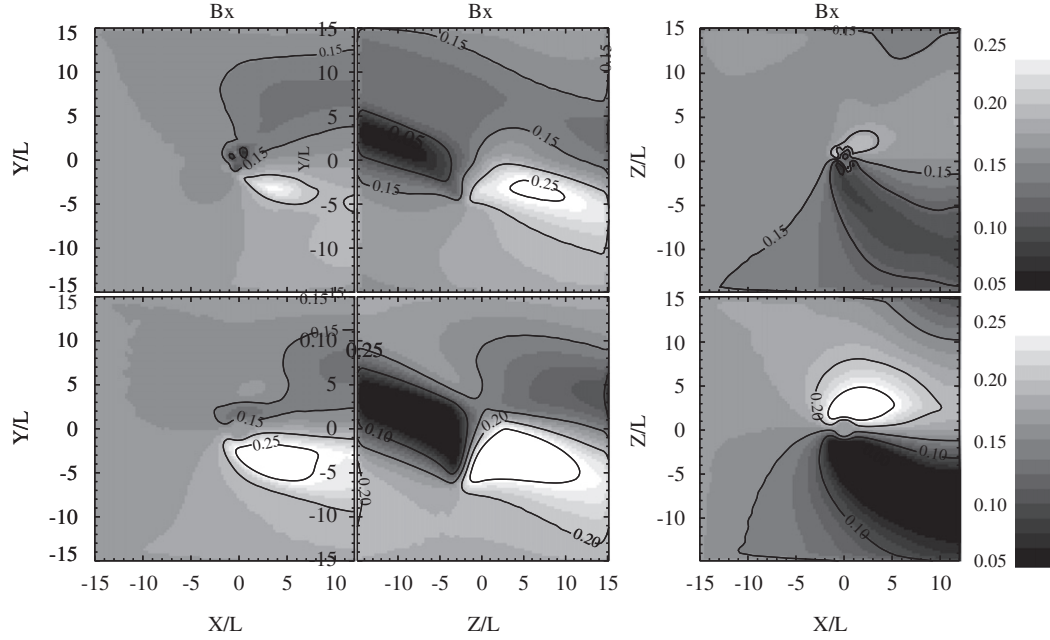


Fig. 5. 2-D cuts of the magnetic field  $B_x$  profile: model A (top) and model B (bottom).

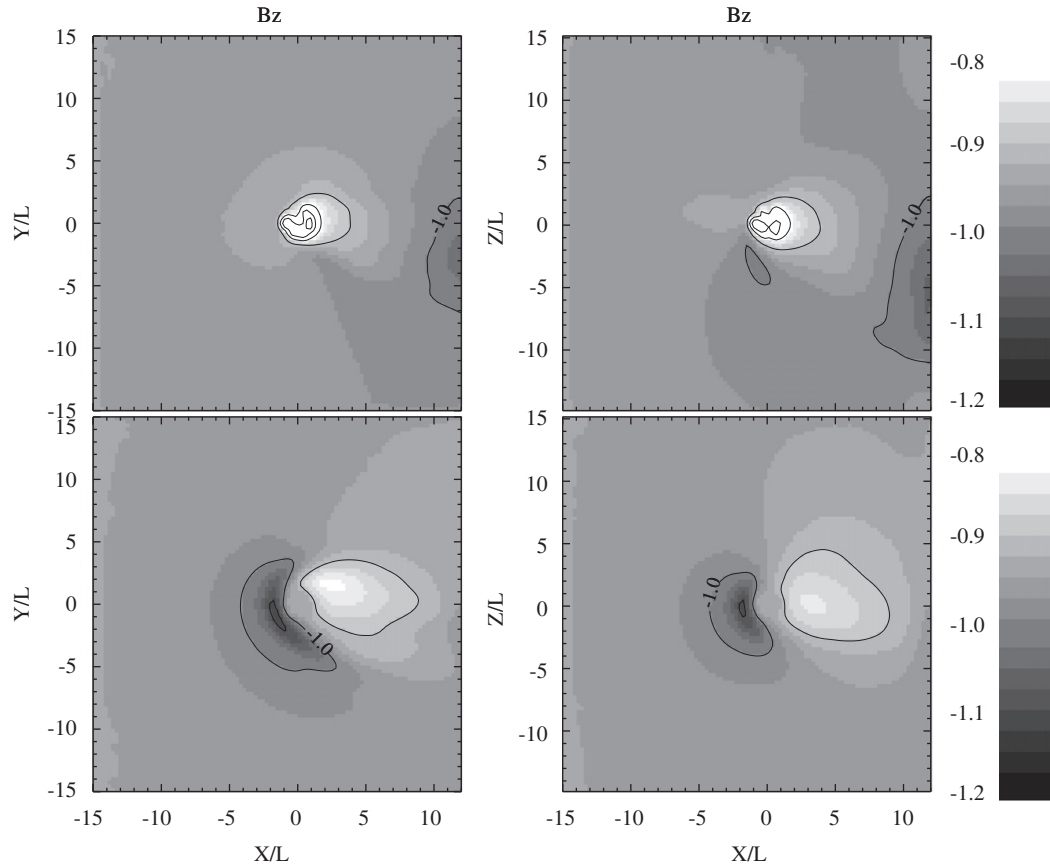


Fig. 6. 2-D cuts of the magnetic field  $B_z$  profiles: model A (top) and model B (bottom).



a buffer zone with a thickness of about  $10 \times \Delta x$ , where a smoothing procedure provides a transition for electromagnetic fields from the perturbed value to the upstream value on the side boundaries (see, e.g., Umeda et al., 2001). This effectively allows Europa-generated Alfvén disturbances to propagate away. The pickup ions exit the computational domain when they intersect the surfaces  $x = 5 \times \Delta x$ ,  $x = DX - 5 \times \Delta x$ ,  $y = 5 \times \Delta y$ ,  $y = DY - 5 \times \Delta y$ ,  $z = 5 \times \Delta z$ ,  $z = DZ - 5 \times \Delta z$ . Thus there is no influx of pickup ions at the side boundaries. At Europa's surface,  $r = R_E \approx 1560$  km, the particles are absorbed. There is no boundary condition for the electromagnetic field; we also use our equations for the electromagnetic field, (see, Eqs. (2), (4) and (9), Lipatov and Combi, 2006) inside the Europa but using the internal conductivity and bulk velocity that are calculated from the particles. In this way the jump in the electric field is due to the variation of the value of the conductivity and bulk velocity across Europa's surface. (Note that the position of Europa is  $x=0$ ,  $y=0$ ,  $z=0$ ). The induced magnetic field from subsurface ocean is not included.

The three-dimensional computational domain has dimensions  $DX=30L$ ,  $DY=30L$ , and  $DZ=27L$ , where  $L$  equals the radius of Europa ( $R_E=1560$  km). We used meshes of  $201 \times 201 \times 201$ , or  $301 \times 301 \times 271$  grid points, and  $5 \times 10^8$  and  $5 \times 10^8$  particles for ions and pickup ions, respectively, for a homogeneous mesh computation. The particle time step  $\Delta t_p$  and the electromagnetic field time step  $\Delta t_{EB}$  satisfy the following condition:  $v_{max}\Delta t_p \leq \min(\Delta x, \Delta y, \Delta z)/8$  and  $v_{max}\Delta t_{EB} \leq \min(\Delta x, \Delta y, \Delta z)/256$ .

The global physics in Europa's environment is controlled by a set of dimensionless independent parameters such as  $M_A$ ,  $\beta_i$ ,  $\beta_e$ ,  $M_{pi}/M_p$ , ion production and charge exchange rates, diffusion lengths, and the ion gyroradius  $\varepsilon = \rho_{ci}/L$ . Here  $\rho_{ci} = U_0/(eB/M_i c) = M_{AC}/\omega_{pi}$  and the ion plasma frequency  $\omega_{pi} = \sqrt{4\pi n_0 e^2/M_i}$ . For real values of the magnetic field, the value of the ion gyroradius is about 80 km, which is calculated from the local bulk velocity. The dimensionless ion gyroradius and grid spacing have the values  $\varepsilon = 0.05$  and  $\Delta x/L = 0.1$ .

## 2.2. Numerical method

We employed a standard particle-in-cell (PIC) method with a homogeneous grid. The time integration of the particle equations of motion uses a leapfrog trapezoid scheme. The time integration of the electromagnetic field equations uses an implicit finite difference scheme (see, e.g., Lipatov, 2002). We used different time steps for particle and field pushing (subcycling). The code was optimized for massively parallel computation using the message passing interface (MPI) and the open multi-processing (OpenMP) environments.

Since the gyroradius scale must be resolved, a grid point spacing of less than one gyroradius is required in order to avoid numerical dispersion and dissipation. On the other hand, good statistics are required, therefore a sufficiently large number of particles per cell have to be used (to obtain low “shot” noise, which manifests itself as fluctuations in the numerical plasma parameters due to a small number of particles per cell).

## 3. Results of Europa's environment simulation

To study the interaction of the plasma torus with the ionosphere of Europa, the following set of Jovian plasma torus and ionosphere parameters were adopted in accordance with the Galileo Europa E4 flyby observational data (Paterson et al., 1999; Khurana et al., 1998; Kivelson et al., 1997; Kivelson et al., 1999): magnetic field,  $B_0=469$  nT and  $\mathbf{B}=(77.6, -140.7, -441.3)$  nT; ratio of specific heats,  $\gamma=5/3$ ; electron betas,  $\beta_{e,0}=0.00011$ ; Alfvén and sonic Mach numbers,  $M_A=0.25$ ;  $M_s=3.66$ .

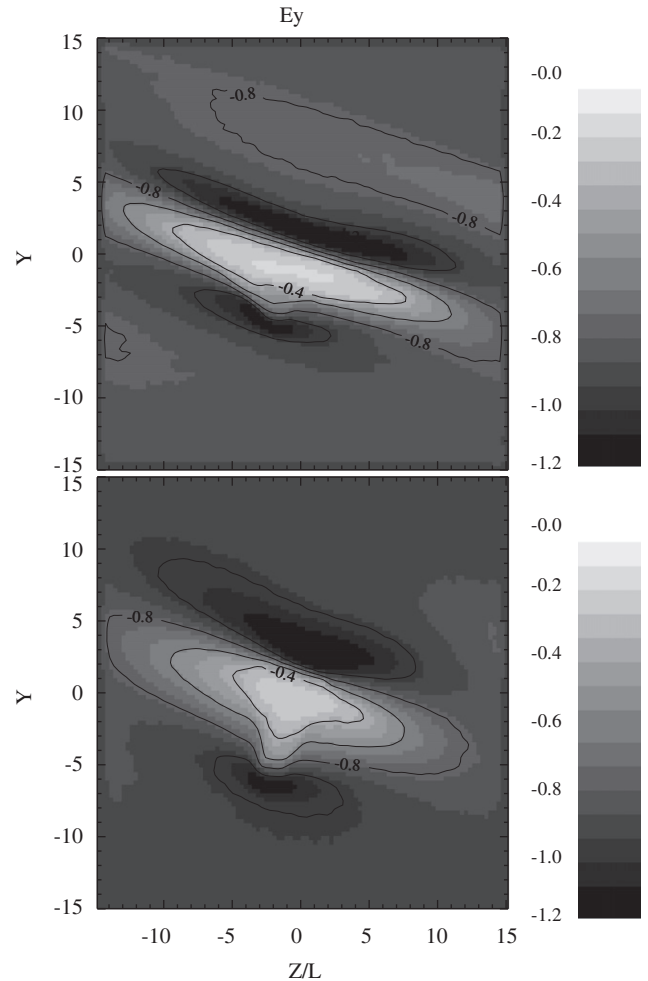
We consider two models for the upstream composition:

Model A (Kabin et al., 1999): upstream (corotation) velocity,  $U_0=90$  km/s;  $V_0=0$  km/s;  $W_0=0$  km/s; background ion densities  $n_{SO^{++}}=35$  cm $^{-3}$ ; ion temperature,  $T_p=90$  eV; ion beta,  $\beta_{SO^{++}}=0.00548$ ; mean ion mass,  $M_{SO^{++}}=48 M_p$ ; mean ion mass,  $(M/Q)_{SO^{++}}=24$ .

Model B (Paterson et al., 1999): upstream (corotation) velocity,  $U_0=105$  km/s;  $V_0=0$  km/s;  $W_0=0$  km/s; background ion densities  $n_{O^{++}}=10$  cm $^{-3}$ ;  $n_{S^{++}}=10$  cm $^{-3}$ ; ion temperature,  $T_i=90$  eV; ion betas,  $\beta_{O^{++}}=0.00548$ ;  $\beta_{S^{++}}=0.00548$ ; mean ion mass,  $M_{O^{++}}=16 M_p$ ;  $M_{S^{++}}=32 M_p$ ; and  $M/Q$  ratio,  $(M/Q)_{O^{++}}=8$ ;  $(M/Q)_{S^{++}}=16$ .

For pickup ions we used the following parameters and/or ranges of parameters: total of the hot pickup ion production rate,  $Q_{O_2^{++},thermal}=1.65 \times 10^{28}$  s $^{-1}$ ; total of the cold pickup ion production rate,  $Q_{O_2^{++},cold}=3.9 \times 10^{26}$  s $^{-1}$ ; mean ion mass,  $M_{pi}=32 M_p$ ; electron pickup and ionosphere betas,  $\beta_{e,pi,02,cold}=0.004$ ,  $\beta_{e,pi,02,thermal}=0.001$ ,  $\beta_{e,iono}=0.001$ ; an effective rate for charge exchange,  $v_{exch}=1.5 \times 10^{-15}$  cm $^2$ ; an effective rate for the photoionization,  $v_{exch}=1.0 \times 10^{-7}$  s $^{-1}$ ; an effective rate for the electron impact ionization,  $v_{exch}=1.8 \times 10^{-6}$  s $^{-1}$ .

The maximum density of the immobile ionosphere,  $n_{iono,R_{iono}}$ , is about  $10 n_{upstream}$ . Note that in the calculation the effective ionosphere scale height,  $\delta_{iono}=10$  km is smoothed over the nearest grid cell and its specific value is not crucial. However, for charge exchange between the ions and atoms we used the



**Fig. 7.** 2-D cuts ( $x=5R_E$ ) of the electric field  $E_y$  profiles: model A (top) and model B (bottom).

analytical formula for the density of the atmosphere without any smoothing.

Let us consider first the case for the global picture of the interaction of the plasma torus with Europa. Figs. 2 and 3 demonstrate the asymmetrical distribution of the pickup ion density (top, model A) and (bottom, model B) in the  $x$ – $y$ ,  $y$ – $z$  ( $x=5R_E$ ) and  $z$ – $x$  planes. The pickup ion motion is determined mainly by the electromagnetic drift. The motion along the magnetic field is due to the thermal velocity and the gradient of the electron pressure. A more significant rotation and wider density profile of the pickup ions were observed in the model A, Figs. 2 and 3 (top). The density profile is slightly disturbed near the side boundaries. However, as already discussed, this perturbation does not affect the region close to Europa. The simulation gives the following total fluxes for the  $O_2^+$  pickup ions (model A):  $1.4 \times 10^{22}$  mol/s (cold) and  $1.75 \times 10^{25}$  mol/s (thermal); (model B):  $0.8 \times 10^{22}$  mol/s (cold) and  $1.0 \times 10^{25}$  mol/s (thermal) across the back boundary  $x=12R_E$ .

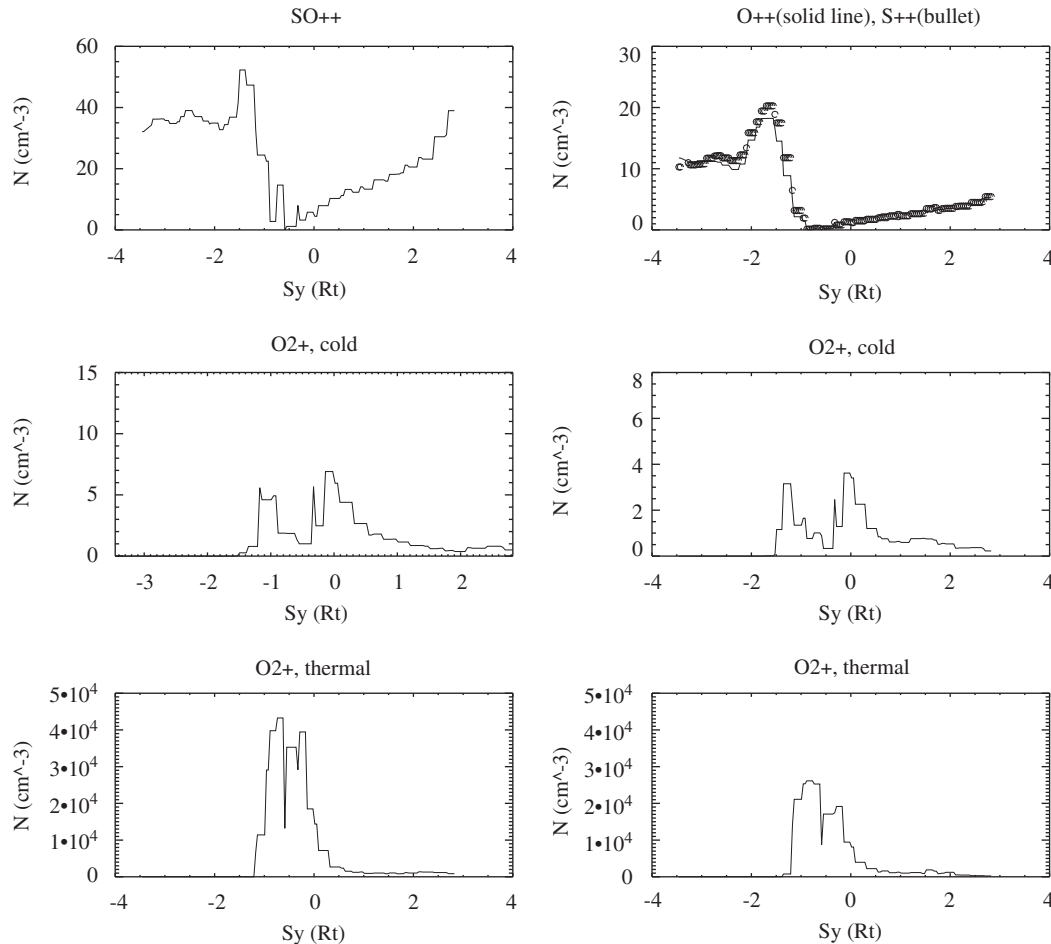
Fig. 4 demonstrates the asymmetrical distribution of the torus plasma ion density in the  $x$ – $y$ ,  $y$ – $z$  ( $x=5R_E$ ) and  $z$ – $x$  planes. One can see the increase of the incoming ion density upstream of Europa. The asymmetrical distribution of the incoming ions in the  $x$ – $y$  planes may be explained by the existence of a strong  $B_z$  component of the upstream magnetic field. One can also see an increasing of the plasma density near Europa due to the formation of a magnetic barrier, Fig. 6 (top and bottom). In model B, this effect is stronger than in model A due to a smaller gyroradius of the incoming ions in model B. In the case of model A the penetration of the incoming ions

into the pickup ion region is deeper because of a weaker coupling than in model B. The inclination of the magnetic field results in an asymmetrical boundary condition for ion dynamics (penetration and reflection) in Europa's ionosphere and an asymmetrical Alfvén wing.

Note that the incoming ions flow around the effective obstacle that is produced by pickup ions and the ionosphere. The pickup ions flow from the “corona” across the magnetic field due to electromagnetic drift, whereas the motion along the magnetic field is determined by the thermal velocity of ions and the electron pressure.

Figs. 5 and 6 show the distribution of the magnetic field,  $B_x$  and  $B_z$ . The asymmetry of the distributions in  $\mathbf{B}$  appears to be caused by the finite gyroradius effects of incoming and pickup ions. A weak perturbation of the magnetic field was observed near the ionosphere of Europa: compression of the upstream magnetic field and decompression in the plasma wake.

Figs. 5 ( $B_x$ —top and bottom, middle sections) and 7 ( $E_y$ —top and bottom) also show the formation of a strong Alfvén wing in the direction of the main magnetic field. Note that the whistler was observed as a leading edge of a wing early in the simulation. Once the simulation stabilized it was replaced by an Alfvén wave. The perturbation of the electric field inside the wings is very strong, and it may affect ion dynamics, so that particles flow around the wings. The formation of the Alfvén wing in a sub-Alfvénic flow near Europa is similar to the formation near Io, which was first studied analytically by Neubauer (1980). The excitation of a whistler wave near a plasma cloud was studied by using a 3-D hybrid simulation by Lipatov (2002). The above



**Fig. 8.** 1-D ion density profiles along the E4 trajectory from simulation. Incoming ions:  $SO^+$ ,  $O^+$  and  $S^+$ . Pickup ions:  $O_2^+$  (cold) and  $O_2^+$  (thermal). Model A (left, Kabin et al., 1999). Model B (right, Paterson et al., 1999).



wave propagation is closely connected with the generation of low-frequency waves by the magnetic harmonic dipole (local source) in the magnetized plasma. The first analytical studies of these effects may be found, for example, in the work by Van'yan and Lipatov (1972, and references therein).

Fig. 8 shows 1-D density profiles of the background and pickup ions along the E4 trajectory of the Galileo spacecraft. One can see a strong plasma void in the center of the plasma wake. There is also a sharp boundary with an overshoot in the density profiles on the left side of the plasma wake, and a smooth boundary layer on the right side, Fig. 8 (top). The density profile for  $\text{SO}^{++}$  is similar to the density profiles for  $\text{O}^{+}$  and  $\text{S}^{++}$  background ions. Fig. 8 (middle and bottom) shows the density profiles for the cold (top) and thermal (bottom)  $\text{O}_2^{+}$  pickup ions. One can see the split structure of the plasma tail. The effect of splitting of the plasma tail was also observed in the hybrid simulation of weak comets (see, e.g., Lipatov, 2002). The general feature of these plasma density is due to the effect of the finite heavy gyroradius.

Fig. 9 shows an example of fluxes of  $\text{SO}^{++}$  (top) and  $\text{O}_2^{+}$  (bottom) ions at the surface of Europa computed from the simulation with model A. One may see the anisotropy of the distribution in the flux for  $\text{SO}^{++}$  due to the finite ion gyroradius. Note that the main component of the external magnetic field is oriented along the  $z$ -axis. The pickup ions form a peak in the flux distribution at the surface near the point  $z=y=0$ .

Fig. 10 demonstrates the comparison of the results of simulation with the E4 Galileo magnetic field data (Kivelson et al., 1999). One can see the difference in the magnetic field profiles, especially for the  $B_x$  and  $B_y$  magnetic field components. We assume that these disagreements may be due to insufficient grid resolution near the surface of Europa and a significant numerical dissipation of the electromagnetic field through the Europa's surface.

One of the possibilities for improving the agreement between the computational model and observation is to include a dipole magnetic field inside Europa that may be induced by the time variation of the background magnetic field. These types of the MHD models were considered in Schiling et al. (2004, 2008) and Liu et al. (2000). We have repeated our simulations (models A and B) but with the magnetic inductive dipole. The value of the magnetic dipole was taken from the paper by Kabin et al. (2001). Fig. 11 shows the magnetic field profile along Galileo's trajectory. One may see an improved agreement between simulation and Galileo's E4 flyby measurements on the second part of the trajectory,  $S_y > 0$ . These simulations do not demonstrate any improvements in the agreement on the first part of the trajectory,  $S_y < 0$ . We have to note here that our present computational model does not provide enough spatial resolution. We also need to use a much larger number of the macro-particles to improve the approximation of the ion velocity distribution. We expect to get good agreement by the choice of the best orientation of the magnetic dipole and the boundary condition for the electromagnetic field. Better spatial grid resolution near Europa and the use of a larger number of the macro-particles will provide a much better resolution in the current system and therefore in the magnetic field configuration near the surface of Europa and the plasma wake. Note that improved plasma behavior resolution may help in the study of the particle-wave interactions, e.g., ion cyclotron wave generation.

Fig. 12 shows the radial cuts for the value of the electric field  $|E|$ , the value of the magnetic field  $|B|$ , the  $|E/B|$  ratio and  $|E/B^2|$  along the  $-x$  (solid line),  $y$  ( $\odot$ ),  $-y$  ( $+$ ),  $z$  ( $*$ ) and  $-z$  ( $\times$ ) directions. This figure allows us to estimate the electromagnetic field near surface of Europa in different locations.

In our future computational models, we plan to include the induced dipole magnetic field with various orientations of the axis of the dipole, the use of a various values of the density of the

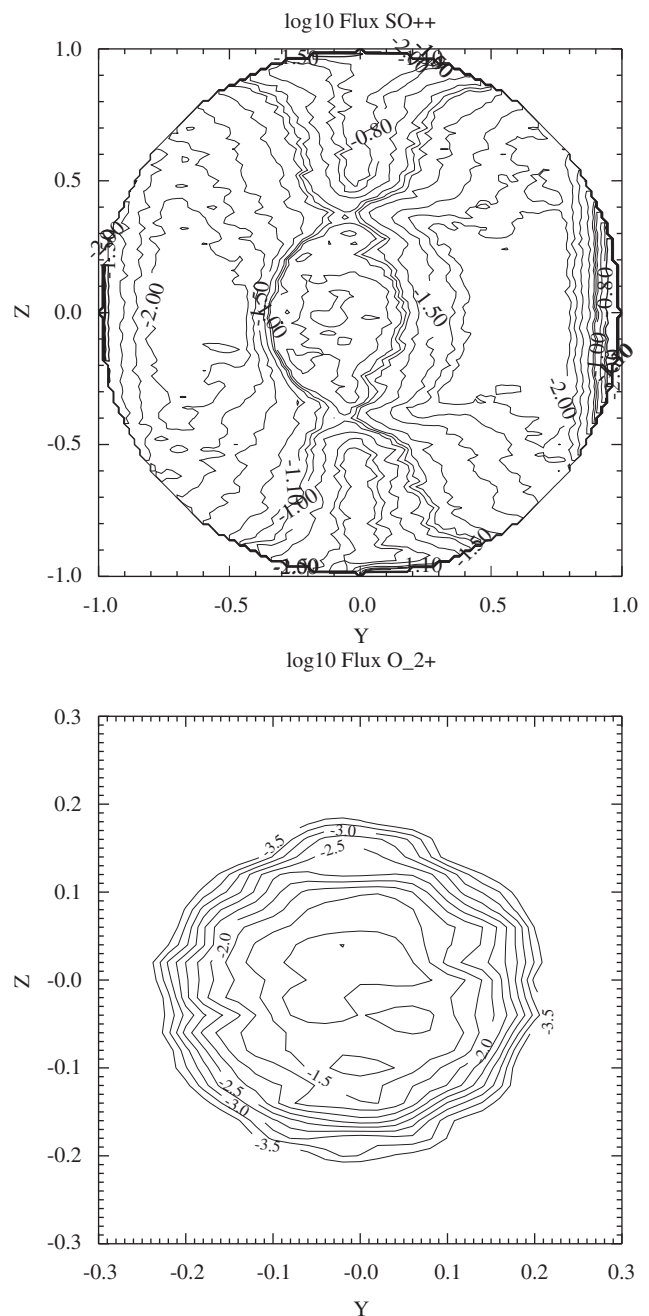
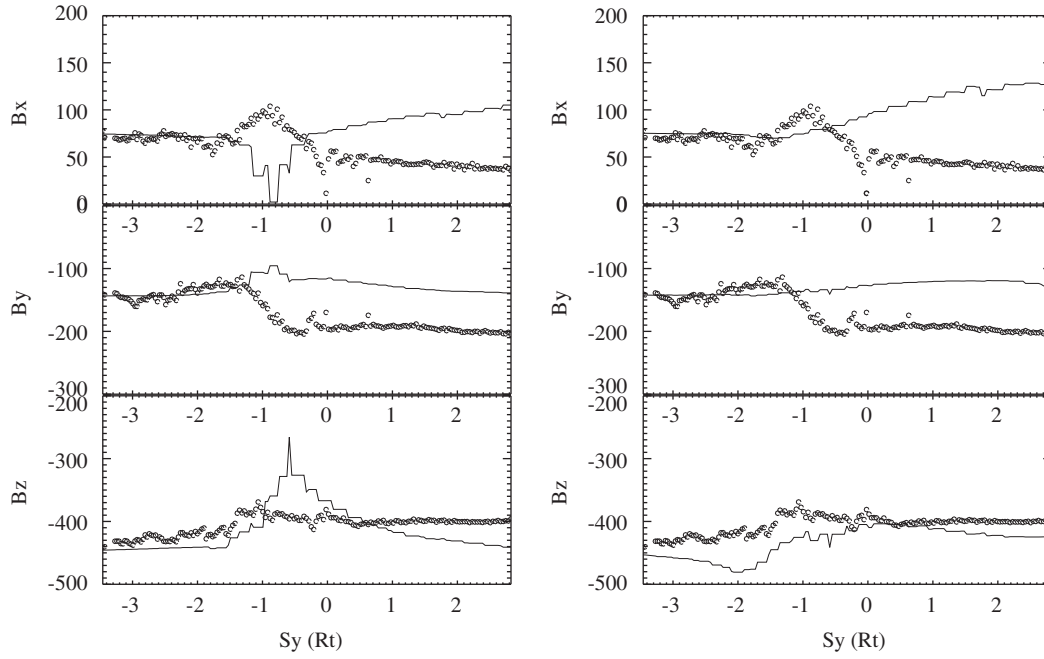
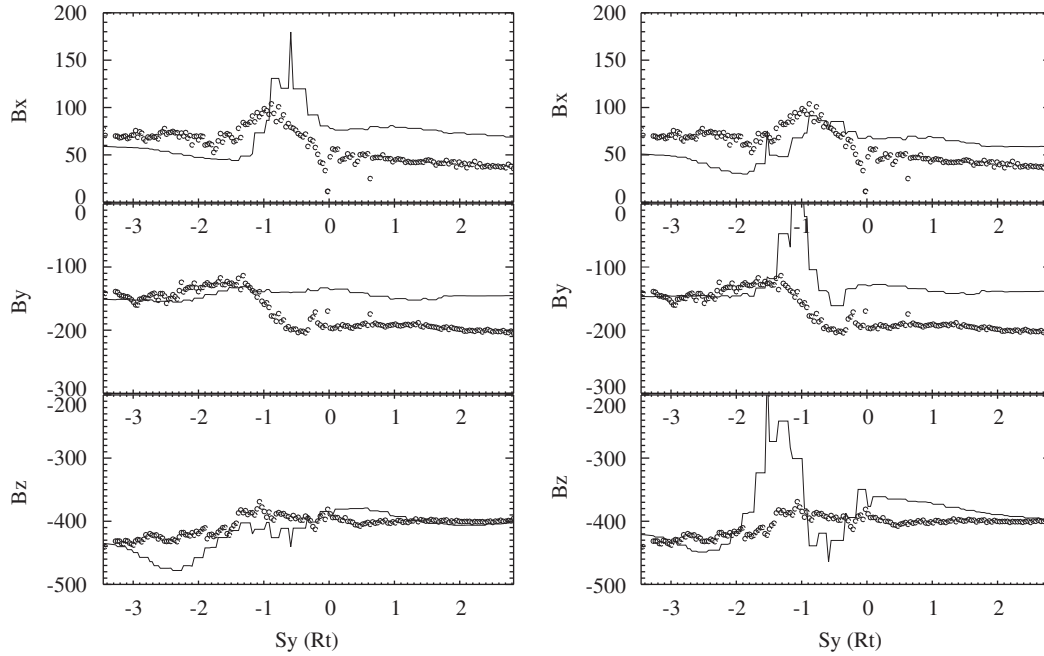


Fig. 9. Example of fluxes of  $\text{SO}^{++}$  (top) and  $\text{O}_2^{+}$  (bottom) ions at the surface of Europa. The fluxes are normalized by the background ion flux,  $n_0 W_0$ .

atmosphere, various values of the electron temperature that plays a key-role in the pickup ion dynamics, and the sputtering processes (Johnson, 1990; Johnson et al., 1998) at the surface of Europa. It will be important to check the possibility of the pickup ion surfing acceleration inside the ionosphere as first reported from an earlier simulation by St.H. Brecht (private communication to J.F. Cooper). This mechanism plays an important role in the pre-acceleration of the ions at the ramp of the collisionless shock (see, e.g., Lee et al., 1996; Zank et al., 1996; Lipatov and Zank, 1999; Lipatov, 2002). We also plan to use a composite grid structure using the “cubed sphere” technique (see, e.g., Koldoba et al., 2002) to improve the resolution of the small scales near the surface of Europa and to increase the size of the computational domain. Note that the larger computational domain allows us to use the



**Fig. 10.** Magnetic field.  $\circ$ —Galileo's E4 flyby measurements (Kivelson et al., 1999); solid line—simulation. Model A (left) and model B (right).



**Fig. 11.** Magnetic field.  $\circ$ —Galileo's E4 flyby measurements (Kivelson et al., 1999); solid line—simulation with m-dipole. Model A (left) and model B (right).

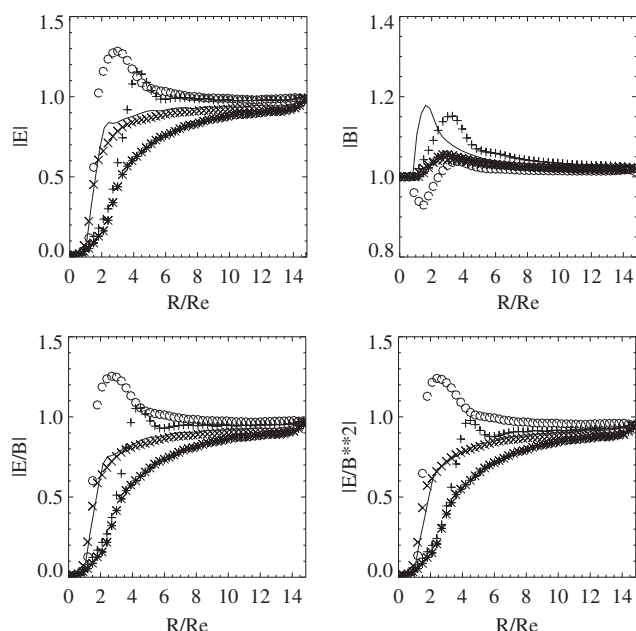
upstream parameters for plasma and electromagnetic field instead of the use of the “damping” boundary condition. However, in the outer region of the computational domain (large size of the cell) we have to use a drift-kinetic approach for ion dynamics since we cannot approximate the ion trajectory there.

#### 4. Conclusions

The hybrid simulation of Europa's plasma environment for E4 encounter with three ion species demonstrated several

features:

- The heavy pickup ions form a structured wake.
- The simulation shows the magnetic field barrier formation near the lobe side of the ionosphere. The formation of the Alfvén wing in the plane of the external magnetic field was also observed.
- The electron temperature plays an important role on plasma structure formation, and in creating the ion fluxes inside the ionosphere.
- Future simulations must use the composite grid structure, e.g., “cubed sphere” or “Yin–Yang” grids (see, e.g., Koldoba et al.,



**Fig. 12.** Radial cuts for  $|E|$ ,  $|B|$ ,  $|E/B|$  and  $|E/B^2|$ . Directions:  $-x$  (solid line),  $y$  ( $\circ$ ),  $-y$  ( $+$ ),  $-z$  ( $\times$ ). Diffusion length near Europa,  $l_d = 1/Re_m = 0.005$ .

2002; Kageyama and Sato, 2004, and references therein) to resolve the multiscale effects near the surface of the outer-planet moons, e.g., Titan, Europa, and the Moon and in the outer plasma environment. These simulations will allow us to study some kinetic wave–particle interaction effects in the plasma wake such as the ion cyclotron waves that were observed in the Galileo flyby mission. These simulations must include the induced magnetic field from a putative subsurface ocean, and the particle trajectory tracing for test particles (e.g., energetic electrons) and later fully kinetic model including electrons.

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