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RESEARCH ARTICLE

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Key Points:

- An inhomogeneity in Europa's global atmosphere generates a pronounced north-south asymmetry in the Alfvén far field
- An Alfvén winglet develops within the main Alfvén wing when an atmospheric inhomogeneity is present
- Magnetic field perturbations during the E26 flyby might be caused by an atmospheric inhomogeneity on Europa's southern hemisphere

Correspondence to:

A. Blöcker,
bloecker@geo.uni-koeln.de

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Europa's plasma interaction with an inhomogeneous atmosphere: Development of Alfvén winglets within the Alfvén wings

Aljona Blöcker¹, Joachim Saur¹, and Lorenz Roth²
¹Institute of Geophysics and Meteorology, University of Cologne, Cologne, Germany, ²School of Electrical Engineering, KTH Royal Institute of Technology, Stockholm, Sweden

Abstract We apply a three-dimensional magnetohydrodynamic (MHD) model to study the influence of inhomogeneities in Europa's atmosphere, as, for example, water vapor plumes, on Europa's plasma interaction with the Jovian magnetosphere. In our model we have included electromagnetic induction in a subsurface water ocean, collisions between ions and neutrals, plasma production and loss due to electron impact ionization, and dissociative recombination. We present a systematic study of the plasma interaction when a local inhomogeneity in the neutral density is present within a global sputtering generated atmosphere. We show that an inhomogeneity near the north or south pole affects the plasma interaction in a way that a pronounced north-south asymmetry is generated. We find that an Alfvén winglet develops within Europa's main Alfvén wing on that side where the inhomogeneity is located. In addition to the MHD model we apply an analytic model based on the model of Saur et al. (2007) to understand the role of steep gradients and discontinuities in the interaction. We compare our model results with the measured magnetic field data from three flybys of the Galileo spacecraft at Europa which included Alfvén wing crossings. Our analysis suggests that the magnetic field might be influenced by atmospheric inhomogeneities during the E26 flyby. The findings of this work will aid in the search for plumes at Europa in future plasma and field observations.

1. Introduction

The scenario of magnetospheric plasma flowing with sub-Alfvénic velocities past a moon with a tenuous atmosphere is a very common interaction scenario in the outer solar system and was frequently studied in the literature [see, e.g., Kivelson et al., 2004]. Jupiter's satellite Europa also experiences such a sub-Alfvénic flow as it is embedded in Jupiter's magnetospheric plasma, which constantly overtakes the moon. Ionization and collisions within the atmosphere and induced fields in Europa's interior modify the plasma environment and drive large currents through the moon's ionosphere. A key feature of the sub-Alfvénic flow past the moon's atmosphere is the development of Alfvén wings. In the rest frame of the moon, standing Alfvén waves are generated which perturb the fields and form a tube-shaped region referred to as the Alfvén wing [see, e.g., Neubauer, 1980; Goertz, 1980]. The Alfvén mode is of particular interest for the understanding of the sub-Alfvénic plasma interaction because it carries field-aligned currents and energy along Jupiter's background magnetic field at the Alfvén velocity in the rest frame of the plasma. The perturbations which occur in the vicinity of the moon map out along the Alfvén characteristics, i.e., along the direction of the group velocity of the Alfvén waves. The atmosphere of the moon is the root cause for the generation of the wings and thus decisively influences the plasma interaction. Therefore, the Alfvénic far field is diagnostic of the moon's atmospheric properties and provides the opportunity to draw conclusions about Europa's atmosphere by studying the velocity and magnetic field in the wings.

Hubble Space Telescope (HST) observations of ultraviolet (UV) oxygen emissions demonstrated the existence of a tenuous molecular oxygen atmosphere around Europa with column densities in the range of $(2-14) \times 10^{18} \text{ m}^{-2}$ [Hall et al., 1995, 1998]. The atmosphere is mostly produced by sputtering processes of its icy surface and radiolysis driven by the energetic particle flux [Johnson, 2004; Paranicas et al., 2001, 2002] and primarily lost by thermal ion sputtering [Saur et al., 1998; Dols et al., 2016]. Saur et al. [2011] discussed the possibility of water vapor plumes to explain asymmetries or inhomogeneities in Europa's UV oxygen emission. Alternatively, emission asymmetries can also be caused by inhomogeneous surface properties

[Cassidy *et al.*, 2007], inhomogeneous solar illuminations [Plainaki *et al.*, 2012, 2013], and/or by Europa's complex plasma interaction with Jupiter's magnetosphere. Roth *et al.* [2016] analyzed a large set of HST observations providing further details on Europa's UV emissions. They showed that the plasma interaction plays an important role in shaping the morphology of Europa's UV emission. The UV emission is brightest near its poles and dimmest near the equator.

Galileo spacecraft radio occultation measurements by Kliore *et al.* [1997] revealed an asymmetric ionosphere with electron densities reaching values on the order of $1 \times 10^4 \text{ cm}^{-3}$ near the surface and a plasma scale height of $240 \pm 40 \text{ km}$ from the surface up to 300 km and of $440 \pm 60 \text{ km}$ above 300 km. Saur *et al.* [1998] showed that electron impact ionization is the main source for the generation of Europa's ionosphere. The newly ionized particles are then accelerated to the velocity of the flowing plasma. The findings of Intriligator and Miller [1982] identified Europa as a source of plasma in Jupiter's middle magnetosphere. The mass outflow is discussed to occur in the form of a mass pickup plasma wake or a transported plasma plume [Russell *et al.*, 1998; Intriligator and Miller, 1982; Eviatar and Paranicas, 2005]. Additionally, Volwerk *et al.* [2001] analyzed ion cyclotron waves driven by positively charged pickup ions in Europa's vicinity showing that similar to Io, Europa provides mass to Jupiter's magnetosphere. From the detection of a Jupiter-surrounding neutral gas torus in the vicinity of Europa's orbit, Mauk *et al.* [2003] and Lagg *et al.* [2003] inferred that Europa is a source of neutral gas in Jupiter's magnetosphere.

In situ measurements by the Galileo spacecraft were obtained during a total of 12 flybys which were extensively studied and modeled focusing on different aspects which modify the plasma interaction with Europa's global atmosphere such as induced fields from a subsurface ocean [see, e.g., Kivelson *et al.*, 1997; Khurana *et al.*, 1998; Kivelson *et al.*, 1999; Zimmer *et al.*, 2000; Schilling *et al.*, 2004, 2007, 2008] and influence of pickup ions [see, e.g., Paterson *et al.*, 1999; Rubin *et al.*, 2015]. Several kinds of models have been used in the past to describe the interaction between Europa's global atmosphere and the magnetospheric plasma: a two-fluid plasma model [Saur *et al.*, 1998], a multispecies chemistry model [Dols *et al.*, 2016], several MHD models [Kabin *et al.*, 1999; Liu *et al.*, 2000; Schilling *et al.*, 2007, 2008; Rubin *et al.*, 2015], and a hybrid kinetic approach [Lipatov *et al.*, 2010, 2013]. Although these models are able to reproduce the overall structure of the measured magnetic field perturbations, some features in the data are still not understood. For example, neither the model results of Schilling *et al.* [2007] nor those of Rubin *et al.* [2015] are able to reproduce some prominent structures such as the double-peak structure in the B_x component in the Galileo Magnetometer (MAG) data during the Alfvén wing crossing of the E26 flyby.

Previous interaction models [e.g., Kabin *et al.*, 1999; Saur *et al.*, 1998; Schilling *et al.*, 2007; Rubin *et al.*, 2015] have focused on the plasma interaction with a global atmosphere without local inhomogeneities while the influence of a local atmospheric inhomogeneity in a global atmosphere on Europa's plasma interaction has not been studied, yet. A prominent feature representing such an atmospheric inhomogeneity in a global atmosphere is the recently discovered water vapor plumes at Europa's south pole [Roth *et al.*, 2014a]. In December 2012, images of Europa's UV aurora by the HST Space Telescope Imaging Spectrograph (STIS) revealed local hydrogen and oxygen emissions in intensity ratios, which are consistent with electron impact excitation of water molecules. Roth *et al.* [2014a] show that the two water vapor plumes with a scale height of $(200 \pm 100) \text{ km}$ and line-of-sight column densities of $\sim 1.5 \times 10^{20} \text{ m}^{-2}$ quantitatively fit the HST/STIS observations. Observations from previous and further HST campaigns did not reveal signatures from plumes in the observations which leaves the occurrence pattern of plumes a major unresolved issue [Roth *et al.*, 2014b].

In the dense local plume region in Europa's global atmosphere ionization and collisions between the magnetospheric and neutral particles are enhanced, and therefore, stronger perturbations are generated which propagate along the magnetic field lines and map out into the Alfvén wing as well. A consequence of the localized region of increased perturbations is the development of a small Alfvén wing within the main Alfvén wing. We will refer to this inner smaller wing as *Alfvén winglet*. Alfvén wings have been introduced and studied in detail dating back to, e.g., Neubauer [1980], Southwood *et al.* [1980], and Goertz [1980]. However, the formation of Alfvén winglets within the Alfvén wings has not been systematically studied before.

The effect of atmospheric inhomogeneities is also important at other moons like Io. Volcanic eruptions on Io locally enhance the neutral density of the atmosphere and thus modify the plasma interaction. A simulation by Roth *et al.* [2011] shows the formation of an Alfvén winglet within the expected main Alfvén wing above

Tvashtar, one of the largest observed volcanic plumes on Io [Spencer *et al.*, 2007]. Since Europa's atmosphere is much thinner we expect dense atmospheric inhomogeneities to affect the Alfvénic far field much stronger compared to Io.

In this paper, we provide the first systematic study of Alfvén winglets and how they are shaped by local atmospheric inhomogeneities. As the plumes were observed only on 1 day and the density and the extent of plumes at Europa are not well known, we will perform a parameter study with different plume densities within Europa's global atmosphere to study the effects on the local plasma interaction, the Alfvén wings, and the Alfvén winglets. We will present both MHD and analytic investigations in comparison with the magnetic field during three flybys of the Galileo spacecraft E17, E25A, and E26. We focus on these three flybys because they crossed the Alfvén wings and thus can be used to investigate atmospheric properties propagated along the wings. The comparison of our simulation results with the MAG data along these trajectories allows us to investigate whether signals in the data can be explained by any local atmospheric inhomogeneity. The findings in this work also provide ideas on how to detect plumes in the plasma measurements during future missions.

2. Two Approaches for the Treatment of the Plasma Interaction

The purpose of our study is to investigate how atmospheric inhomogeneities such as plumes influence the plasma interaction. We use two different approaches to describe the plasma interaction. The first approach is carried out with a three-dimensional single-fluid MHD model. We apply numerical simulations to self-consistently calculate the plasma interaction with Europa's atmosphere. The model results are used to study the influence of an atmospheric inhomogeneity on the overall structure of Europa's plasma environment and to reproduce the key features of the measured magnetic field data by the Galileo spacecraft.

The second approach is an analytic model. The purpose of our analytic study is to discuss physical effects due to small-scale gradients in the local inhomogeneities or in the sharp boundary of Europa, which cannot be precisely resolved with the MHD model due to numerical diffusion and viscosity. Both approaches are also used to examine if signatures of an atmospheric inhomogeneity are detectable and present in the measured Galileo magnetic field data during the flybys, whose trajectories crossed the Alfvén wings. The analytic model provides an idealized description of the sub-Alfvénic plasma interaction and thus is not applicable to quantitatively reproduce all the features of the measured data, but it provides a good method to identify possible signatures from localized atmospheric inhomogeneities. With the analytic calculations and their geometrical simplifications, the resulting magnetic field and plasma signatures can be related in a simple and direct way to their physical causes.

2.1. Magnetohydrodynamic Model

The charged particles in the orbit of Europa can be subdivided into cold plasma and energetic particles. The MHD approach is a suitable method to describe the interaction of the cold bulk plasma with Europa's atmosphere. The energetic ions which can have gyroradii >500 km [Sittler *et al.*, 2013] are not included in the MHD approach. At keV energies individual particle motions become important and the particles cannot be treated as a fluid anymore [Paranicas *et al.*, 2009]. The energetic particles affect mainly the thermal plasma pressure but have little effects on the momentum and force balance of the plasma flow. This balance shapes the flow and magnetic field environment around Europa. The plasma beta in our simulations is ~ 0.05 implying that the thermal plasma pressure has a minor effect on the plasma interaction. The pressure of energetic ions (20 keV–100 MeV) is 12 nPa [Kivelson *et al.*, 2009]. Including the energetic ions, the plasma beta rises to ~ 0.1 , which indicates that the pressure does not play a key role in shaping the interaction.

The gyroradius of the thermal ions is approximately 8 km and the ion cyclotron frequency is 0.5 Hz [Kivelson *et al.*, 2004]. This gyroradius is much smaller than typical scales of the interaction, i.e., the radius of Europa, the scales of the atmosphere, or the scales of the plumes under consideration here. Similarly, the period of ion cyclotron motion (2 s) is much smaller than typical convection time scales for the plasma to pass the object of 30 s. The dominant sources which drive Europa's interaction are ionization and charge exchange, which are commonly referred to as pickup processes, and the elastic collision between ions and neutrals. These effects modify the mass, momentum, and energy density of the fluid and are the root cause of the magnetic field perturbations. The effects of these processes are well resolved in MHD or fluid models as long as the gyroradius is smaller than the typical length scales of the interaction, and the period of cyclotron motion is smaller than the typical time scales of the interaction (see, for example, discussion in chapter 7 of Baumjohann

and Treumann [1996] on the applicability of the MHD approach). The inclusion of pickup and elastic collisions in fluid models has been described, e.g., in Schunk and Nagy [2000] and Neubauer [1998], and their principal effects in previous MHD models have been demonstrated in, e.g., Kabin *et al.* [1999], Liu *et al.* [2000], and Schilling *et al.* [2007, 2008]. Its physical effects are rigorously discussed, e.g., in Vasyliūnas [2016]. In summary, the MHD approach is well suited to describe the global plasma interaction of Jupiter's magnetosphere with Europa's atmosphere and its ionosphere.

We use a Cartesian and a spherical coordinate system, both centered at Europa. The Cartesian system is the EPhiO system with its x axis along the flow direction of the corotational plasma, the z axis is parallel to Jupiter's spin axis, and the Jupiter-facing y axis completes the right-handed system. The spherical coordinate system is described by the radius r , the colatitude θ measured from the positive z axis, and the longitude ϕ measured from the positive y axis in direction to the negative x axis.

2.1.1. Model Equations

The one-fluid MHD equations which we apply have been derived from a set of two-fluid equations for ions and electrons where the sources according to mass loading, plasma loss, and collisions have been included [e.g., Schunk, 1975; Schunk and Nagy, 2000]. In Appendix A1, we applied a scale analysis of each term in the one-fluid MHD equations similar to Chané *et al.* [2013] to determine which of these terms can be neglected without changing the important physical processes of the model. The resultant set of MHD equations are then given by

$$\partial_t \rho + \nabla \cdot (\rho \underline{v}) = (P - L)m_i \quad (1)$$

$$\rho \partial_t \underline{v} + \rho \underline{v} \cdot \nabla \underline{v} = -\nabla p + \underline{j} \times \underline{B} - \rho(v_{in} + v_{ex})\underline{v} - Pm_i \underline{v} \quad (2)$$

$$\partial_t \underline{B} = \nabla \times (\underline{v} \times \underline{B}) \quad (3)$$

$$\partial_t \epsilon + \nabla \cdot (\epsilon \underline{v}) = -p \nabla \cdot \underline{v} + \frac{1}{2} \rho v^2 \left(\frac{P}{n} + v_{in} + v_{ex} \right) - \epsilon \left(\frac{L}{n} + v_{in} + v_{ex} \right) \quad (4)$$

with the plasma mass density ρ , the plasma bulk velocity $\underline{v}$, the magnetic field $\underline{B}$, the internal energy density ϵ , which is related to the plasma thermal pressure p through $\epsilon = 3/2 p$, the plasma particle density n , the ion mass m_i , and the Boltzmann constant k_B . For the calculation of $p = nk_B(T_e + T_i)$ we consider the electron temperature T_e and the ion temperature T_i . The current density $\underline{j}$ is determined via Ampère's law $\underline{j} = \frac{1}{\mu_0} \nabla \times \underline{B}$ with the vacuum permeability μ_0 . The model takes into account the produced and lost number of charged particles per time in the plasma production rate P and loss rate L . In the momentum equation (2) we consider the change of the plasma bulk velocity via collisional momentum exchange between the atmosphere and the magnetospheric plasma ($\rho(v_{in} + v_{ex})\underline{v}$) and ionization ($Pm_i \underline{v}$). The parameters v_{in} and v_{ex} are the ion-neutral collision frequency and the charge exchange frequency, respectively. The last two terms on the right-hand side of equation (4) represent the change of internal energy density due to elastic collisions, charge exchange, ionization, and recombination. The temperature of the neutrals ($T_n \approx 130$ K on the dayside region [Shematovich *et al.*, 2005]) can be neglected for the plasma interaction compared with the plasma temperature of about 1160×10^3 K [Kivelson *et al.*, 2004]. Quantitative expressions for the source and loss terms are provided and explained in detail in section 2.1.3. The ratio of specific heats is assumed to be 5/3. The average mass of the upstreaming magnetospheric plasma is $\tilde{m}_i = 18.5$ amu [Kivelson *et al.*, 2004]. The magnetospheric electrons at Europa's location consist mainly of two populations, the thermal and the suprathermal populations with temperatures of $k_B T_{th} = 20$ eV and $k_B T_{sth} = 250$ eV [Sittler and Strobel, 1987; Johnson *et al.*, 2009], respectively. The number density of the thermal electrons n_{th} varies with Europa's position in the plasma sheet. For the number density of the suprathermal electrons n_{sth} we use the ratio $n_{sth}/n_{th} \approx 5\%$ [Bagenal *et al.*, 2015]. Based on charge neutrality, the total magnetospheric electron number density relates to the total ion number density through an effective ion charge of $z_c = 1.5$ [Kivelson *et al.*, 2004]. The upstream plasma mass density thus can be written as

$$\rho_0 = \tilde{m}_i n_i = \tilde{m}_i (n_{th} + n_{sth}) / z_c \quad (5)$$

In our model singly charged ions are produced in the ionosphere with $m_i = m_{O_2^+} = 32$ amu.

2.1.2. Neutral Atmosphere and Local Atmospheric Inhomogeneities

We prescribe Europa's molecular oxygen atmosphere with an analytic expression. We apply a radially symmetric description of the global atmosphere. The global distribution of the neutral atmosphere is observationally not very well constrained, but there are several predictions about global asymmetries in the sputtering atmosphere. Atmospheric modeling suggests that sputtering decreases from the trailing to the leading hemisphere and depends both on solar illumination and plasma impact direction [e.g., *Pospieszalska and Johnson*, 1989; *Plainaki et al.*, 2013]. We do not consider in our model a global asymmetry of the atmosphere compared to, e.g., *Schilling et al.* [2007] or *Rubin et al.* [2015], since our focus is on the influence of local atmospheric inhomogeneities. Therefore, we keep the global atmosphere as simple as possible to better demonstrate the effects of the localized inhomogeneity. The number density of the radially symmetric sputtering atmosphere is given by

$$n_A(r) = n_{A,0} \exp \left[- \left(\frac{h}{H_0} \right) \right] \quad (6)$$

with surface density $n_{A,0}$, scale height H_0 , and altitude $h = r - R_E$ above the surface (with Europa's radius $R_E = 1569$ km).

Following *Roth et al.* [2014a] the density profile of the atmospheric inhomogeneity is assumed to be a function of the altitude h and the angular distance from its center $\tilde{\theta}(\theta, \phi)$ of the form

$$n_{ap}(h, \tilde{\theta}) = n_{ap,0} \exp \left[- \left(\frac{h}{H_h} \right)^\alpha - \left(\frac{\tilde{\theta}}{H_\theta} \right)^2 \right]. \quad (7)$$

$n_{ap,0}$ is the surface number density of the neutral gas in the center of the inhomogeneity, H_h is the scale height, and H_θ is the angular scale of the latitudinal extent. The factor α varies in our model from 1 to 2, with $\alpha = 1$ representing the hydrostatic case with a constant scale and $\alpha = 2$ representing a Gaussian structure varying with altitude. The parameters $n_{A,0}$, $n_{ap,0}$, H_h , and H_θ are treated as free parameters and are varied among different simulation runs. The neutral number density is given by $n_n(r, \theta, \phi) = n_A(r) + n_{ap}(r, \theta, \phi)$. The scale height of the atmosphere H_0 is assumed to be 100 km for all simulations. The surface number density $n_{A,0}$ varies between $2 \times 10^{13} \text{ m}^{-3}$ and $14 \times 10^{13} \text{ m}^{-3}$ resulting in an O_2 column density of $(2-14) \times 10^{18} \text{ m}^{-2}$.

2.1.3. Plasma Sources and Losses

The main ionization process in Europa's atmosphere is electron impact ionization, which is more than 1 order of magnitude larger than photoionization [*Saur et al.*, 1998]. Therefore, we only include electron impact ionization in our MHD model. The production rate for the electron impact ionization of O_2 is calculated from

$$P = f_{\text{O}_2}(T_e) n_{\text{ms}} n_n, \quad (8)$$

where $f_{\text{O}_2}(T_e)$ is the electron impact ionization rate of O_2 for a specific electron temperature T_e and n_{ms} is the number density of the magnetospheric electrons. The calculation of $f_{\text{O}_2}(T_e)$ is given in the Appendix A2 in equation (A20). The temperature of the magnetospheric electrons T_e is not calculated self-consistently. However, to avoid overestimation of the plasma production the ionization process in our model is restricted by the amount of electron energy which possibly can enter Europa's atmosphere. The total electron energy flux into the atmosphere is controlled by the strength of the plasma interaction (see Appendix A2). We assume an electron fluid with an averaged temperature from the thermal and suprathermal populations given by

$$T_e = \frac{n_{\text{th}} T_{\text{th}} + n_{\text{sth}} T_{\text{sth}}}{n_{\text{th}} + n_{\text{sth}}}. \quad (9)$$

We discriminate between the hot magnetospheric and the newly created ionospheric electrons, which are produced by electron impact ionization. They generate two populations of electrons that are energetically different and hence their treatment in the model has to be different [*Schilling et al.*, 2007]. The separation of the magnetospheric and ionospheric electrons is done by the method presented in *Schilling et al.* [2007, 2008]. The cooler ionospheric electrons with temperatures of about 0.5 eV [*Johnson et al.*, 2009] do not contribute to the ionization process. The evolution of the number density of the ionospheric electrons is calculated by equation (1). We solve a separate continuity equation for the number density of the magnetospheric electrons n_{ms}

$$\partial_t n_{\text{ms}} + \nabla \cdot (n_{\text{ms}} \mathbf{v}) = 0. \quad (10)$$

The number density of the magnetospheric electrons does therefore not increase due to electron impact ionization.

Dissociative recombination is the sink of plasma particles in our model. Molecular ions recombine with electrons. The loss process involving magnetospheric electrons is negligible because of their high temperatures. We use the dissociative recombination rate coefficient for O_2^+ given in *Schunk and Nagy* [2000]:

$$\alpha_{\text{rec}}(T_e) = 2 \times 10^{-13} \left(\frac{300}{T_e} \right)^{0.7} \text{ m}^3 \text{ s}^{-1}. \quad (11)$$

For the loss rate we apply the expression adopted from *Saur et al.* [2003]:

$$L_{\text{rec}} = \begin{cases} \alpha_{\text{rec}} n_e (n - n_0) & \text{for } n > n_0 \\ 0 & \text{for } n < n_0 \end{cases}. \quad (12)$$

When the plasma number density $n = \rho/\bar{m}_i$ decreases below the background ion density $n_0 = \rho_0/\bar{m}_i$ with the unperturbed plasma mass density ρ_0 , then the dissociative recombination is set to zero. The reason is that the plasma outside of Europa's ionosphere mostly consists of atomic ions with very small recombination rates which can be neglected on the scales of Europa's interaction, while the plasma in the ionosphere consists of molecular ions with large dissociative recombination rates.

We implement the elastic collisions between ions and neutrals by introducing the average ion-neutral collision frequency

$$\nu_{\text{in}} = 2.6 \times 10^{-15} n_n \sqrt{\frac{\alpha_0}{\mu_a}} \text{ s}^{-1} \quad (13)$$

from *Banks and Kockarts* [1973]. α_0 is the polarizability of the neutral gas in units of 10^{-24} cm^3 and $\mu_a = \frac{m_{O_2^+} m_{O_2}}{m_{O_2^+} + m_{O_2}} = \frac{1}{2} m_{O_2^+}$ is the reduced mass in amu. The polarizability of O_2 is given by $\alpha_0 = 1.59$ [*Banks and Kockarts*, 1973].

Charge exchange plays an important part in the calculation of the energy balance and the momentum, but it does not affect the plasma density. In our model we use the ion-neutral charge exchange collision frequency

$$\nu_{\text{ex}} = 1.7 \times 10^{-19} n_n \sqrt{T_i + T_n} (10.6 - 0.76 \log_{10}(T_i + T_n))^2 \text{ s}^{-1}, \quad (14)$$

for the reaction $O_2^+ + O_2 \rightarrow O_2 + O_2^+$ derived by *Banks* [1966]. Charge exchange reactions between O_2^+ ions and their parent O_2 molecules depend explicitly on the energy of the impacting ion. The ion temperature in equation (14) is calculated through the internal energy density equation (4) via the relation $\epsilon = \frac{3}{2} n k_B (T_i + T_e)$.

2.1.4. Induction in a Subsurface Water Ocean

Due to the tilt of Jupiter's magnetic moment with respect to its spin axis of $\sim 10^\circ$, the x and y components of the background magnetic field periodically vary at Europa's location. This results in an inducing field with Jupiter's synodic period of ~ 11.1 h. The variability of the Jovian background magnetic field including the effects of the magnetospheric current sheet is expressed in our model by

$$B_{x,0}(\lambda_{\text{III}}) = -84 \text{ nT} \sin(\lambda_{\text{III}} - 200^\circ), \quad (15)$$

$$B_{y,0}(\lambda_{\text{III}}) = -210 \text{ nT} \cos(\lambda_{\text{III}} - 200^\circ) \quad (16)$$

with system-III-longitude λ_{III} [*Schilling et al.*, 2007]. The time-varying inducing field drives currents in Europa's subsurface ocean and thus generates a time-varying induced magnetic dipole field. Assuming a radially symmetric ocean and a spatially homogeneous induced field, the resultant induced field is dependent on the ocean's conductivity, the ocean's thickness, and the thickness of the crust between Europa's surface and the ocean. The effect of induction in the subsurface conducting water layer on the magnetic field is included in the inner boundary conditions at the surface of Europa (see section 2.1.6). The derivation of the induced dipole field is described in the work of, e.g., *Zimmer et al.* [2000] and *Saur et al.* [2010]. We assume an ocean that is 100 km thick and lies 25 km beneath the surface with a conductivity of 0.5 S/m according to the findings of *Schilling et al.* [2007].

2.1.5. Numerics, Boundary Conditions, and Initial Conditions

To solve the set of the differential equations (1)–(4), we apply a modified version of the publicly available ZEUS-MP MHD code. ZEUS-MP is a multiphysics, massively parallel, message-passing code for astrophysical fluid dynamics [Norman, 2000], which solves the single-fluid, ideal MHD equations in three dimensions. The code utilizes a staggered-grid finite-difference scheme and the second-order accurate, monotonic advection scheme. In addition, the code applies a combination of the Constraint Transport algorithm and the Method of Characteristics treatment for Alfvén waves. The solution of the differential equations is computed time forward. The time step of the physical processes is controlled by the Courant-Friedrichs-Lewy criterion. A detailed description of the algorithms used in ZEUS-MP can be found in Stone and Norman [1992] and Hayes et al. [2006].

For our numerical simulations, we use a spherical grid in order to facilitate the use of the inner boundary condition explained below. The model domain extends to $20 R_E$ from Europa's center in radial direction. The spherical grid consists of $160 \times 120 \times 120$ (r, θ, ϕ) cells. The angular resolution of the grid in θ and ϕ is equidistant with $\Delta\theta = 1.5^\circ$ and $\Delta\phi = 3^\circ$. The radial resolution is not equidistant and increases by a factor of 1.022 from cell to cell from the inner boundary ($r = 1 R_E$) to the outer boundary ($r = 20 R_E$). The resolution at the surface is chosen to be 21 km. The simulation is performed until the Alfvén wings reach the outer boundary and approximately steady state solution in the vicinity of Europa is reached. In this way, reflections of the Alfvén waves from the outer boundary are avoided. The typical time needed for the corotation flow at 104 km/s to cross Europa's diameter is 30 s. With an Alfvén velocity of 350 km/s the Alfvén wave needs about 90 s to reach the outer boundary. Flow and magnetic perturbations do not evolve noticeably after 90 s in our simulation runs. The ionosphere is not in chemical equilibrium but in a strongly advection-dominated equilibrium. From equation (1) we can estimate an ionization time scale in the model by $\sim \frac{1}{f_{\text{imp},0} n_A} \approx 1$ s with $f_{\text{imp},0}(100 \text{ eV}) = 8 \times 10^{-14} \text{ m}^3 \text{ s}^{-1}$ and $n_A(h = 100 \text{ km})$ the neutral number density in a radial distance of 100 km; therefore, the equilibrium of the neutral atmosphere is assured in our model.

2.1.6. Inner and Outer Boundary Values

Our simulation domain has two boundary areas, namely the outer sphere at $r = 20 R_E$ and the inner sphere at $r = 1 R_E$. In our numerical simulations, the outer boundary is not a real boundary in the sense that physical properties abruptly change or jump. We apply open boundary conditions for the four MHD variables ρ , e , $\underline{v}$, and $\underline{B}$ at the outer boundary. At the downstream region of the outer boundary ($\phi > 180^\circ$) the outflow method is used; i.e., the plasma quantities are extrapolated from the grid cells near the boundary to the boundary cells. At the upstream region ($\phi \leq 180^\circ$) the inflow method is applied; i.e., all plasma quantities are held constant. At the inner boundary, i.e., the surface of Europa, plasma is assumed to be absorbed, which we implement by open boundary conditions for ρ , e , and $\underline{v}$ by an outflow method. The radial component of the plasma bulk velocity v_r is constrained in the way that $v_r \leq 0$ so that plasma does not flow out of the surface (see also discussion in Duling et al. [2014]). Europa's icy surface is not only absorbing but also possesses a negligible electrical conductivity. The insulating nature of the surface does not allow electric currents to penetrate the icy surface. Boundary conditions for the magnetic field have been derived by Duling et al. [2014] ensuring that there is no radial electric current. The boundary condition is constructed in a way that it also can consistently include any time-dependent internal potential fields from below the surface, e.g., caused by induction in an ocean below the nonconducting ice crust. The inner and outer boundary values for our simulations are presented in Table 1.

2.2. Analytic Approach

The basis of our analytic studies is a model for sub-Alfvénic asymmetric magnetospheric interaction developed for Saturn's moon Enceladus by Saur et al. [2007], which we modify and expand for Europa's plasma interaction. The model is based on perturbation theory for Alfvénic Mach numbers $M_A \ll 1$. For a given electrical conductivity distribution exhibiting a north-south asymmetry, Saur et al. [2007] derive an equation for the electric potential on the assumption that the magnetic field perturbations are significantly smaller than the background magnetic field. Therefore, the magnetic field is assumed to be spatially constant. Due to the very large electric conductivity parallel to the magnetic field lines, the background magnetic field lines are isolines of the electric potential [Neubauer, 1998; Saur et al., 1998]. Consequently, the electric potential is reduced to two coordinates perpendicular to the background field. Plasma flow, electric current, and the resultant magnetic field perturbations can be calculated from the electric potential. The derivation of the electric potential is similar to previous derivations, e.g., Wolf-Gladrow et al. [1987] and Neubauer [1980, 1998], with the exception that on the field lines tangent to the nonconducting body, a new jump condition for the electric field

Table 1. Initial and Boundary Condition Values and Calculated Parameters in the EPHIO System

Model Scenario/ Flyby	$\underline{B}_0$ (nT)	$\underline{v}_0$ (km/s)	ρ_0 (amu/m ⁻³)	ϵ_0^a (nPa)	M_A	Σ_A (S)
General model I	(0, 0, -450)	(104,0,0)	4.93×10^8	0.56	0.24	1.75
General model II	(0, -210, -450)	(104,0,0)	4.93×10^8	0.56	0.21	1.60
E17	(73, -100, -425)	(104,0,0)	1.73×10^9	1.97	0.45	3.11
E25A	(-7, -209, -382)	(104,0,0)	8.60×10^8	1.47	0.32	2.33
E26	(-22, 203, -380)	(104,0,0)	4.93×10^8	0.56	0.25	1.82

$$^a \epsilon_0 = 3/2 n_0 k_B (T_e + T_{i,0}) \text{ with } k_B T_{i,0} = 100 \text{ eV [Kivelson et al., 2004].}$$

due to the north-south asymmetry had to be introduced [Saur et al., 2007, equation (9)]. These authors derive a two-dimensional elliptic differential equation for the electric potential Φ . The magnetic field is not treated self-consistently and is given by the constant homogeneous background magnetic field $\underline{B}_0$.

Saur et al. [2007] show that both hemispheres of Enceladus, which are not directly linked together due to the blockage of the solid body, are electromagnetically coupled through field-aligned currents that flow tangent to the solid body. The coupling is due to the fact that the field lines intersecting the moon lie on different potentials of the northern and southern hemispheres of the moon while field lines not intersecting the moon lie on the same potential in both hemispheres. This results in the generation of a hemisphere coupling system confined to surface currents along field lines tangent to the solid body. The hemisphere coupling is accompanied by magnetic field discontinuities across the flux tube as predicted and observed at Enceladus [Saur et al., 2007; Simon et al., 2011, 2014]. The hemisphere coupling currents are delta currents, i.e., an infinitely thin sheet of current, within the MHD framework and thus lead to sharp rotational discontinuities. These delta currents are generated because the electric fields on field lines north and south of the moon differ and thus the electric fields jump across the flux tube enveloping the moon. In the region outside the flux tube, the field lines are isopotential lines, the currents are symmetric in the northern and southern far field for identical Alfvén conductance Σ_A , and no hemisphere coupling currents can be driven.

For the derivation of our analytic model, we use a coordinate system with the x axis pointing along the unperturbed plasma flow, the z axis is antiparallel to the background magnetic field, and the y axis completes the right-handed coordinate system and is pointing toward Jupiter. We call it the EPHIB coordinate system.

2.2.1. Analytic Model for Europa's Electrodynamic Interaction

The model of Saur et al. [2007] developed for Enceladus but here used for Europa needs to be extended to take a global atmosphere into account. With our modifications of the model we are able to study the Alfvén winglets inside of the Alfvén wings. The electric potential depends on the ionospheric conductances. Therefore, we develop a model of the conductance profile of the moon's ionosphere. $\Sigma_{p,H}$ are the ionospheric Pedersen and Hall conductances, which are obtained by the integration of the Pedersen and Hall conductivities $\sigma_{p,H}$ along the direction of the background magnetic field, i.e.,

$$\Sigma_{p,H}(x, y) = \int_{z_0}^{z_i} \sigma_{p,H}(x, y, z) dz. \quad (17)$$

Note, that in the analytic model the background magnetic field lines coincide with the isolines of the electric potential. So the integration is performed along the field lines (over z) from the equatorial plane or the moon's surface z_0 out to a distance z_i where the conductivities vanish (similar to previous calculations of the conductances in sub-Alfvénic interactions, e.g., Neubauer [1998], Saur et al. [1999], and Kivelson et al. [2004]).

The black line in Figure 1 sketches Europa's Pedersen conductance profile for a radially symmetric atmosphere similar to Figure 6 in the work of Neubauer [1998]. As the neutral density decreases exponentially, we assume an exponential profile for the ionospheric conductivities $\sigma_{p,H} \sim \exp(h/\tilde{H})$ with the altitude h and the effective scale height $\tilde{H}$ (see Appendix B). It shows minimum conductances above the pole and maximum conductances at the moon's diameter. The variation of Σ_p (and Σ_H) arises due to the change of the length of the integration path along the magnetic field lines through the atmosphere (see equation (17)), which is shortest at the poles. At the field lines tangent to Europa given by r_s two peaks occur due to the sudden change of the integration path through the atmosphere [Neubauer, 1998]. The magnetic field lines are not connected to the

Figure 1. (top) Pedersen conductance profile $\Sigma_p(x) = \int_{z_0}^{z_i} \sigma_{p,H}(x, z) dz$ (black line), see, e.g., Neubauer [1998] and Simon [2015]. (bottom) The integration is performed from the surface (green line) or the equatorial plane ($z_0 = 0$) along z up to the region where the conductivities vanish (z_i), shown by the dark blue line, over one half-space for a symmetric atmosphere. An exponential conductivity profile was assumed ($\sigma_p \sim \exp\left(\frac{h}{H_e} + \frac{h}{H_a}\right)$; see Appendix B). The conductance achieves its maximum where the field lines are tangent to Europa, i.e., $x = r_s$. It has a local minimum at the poles because of the shortest integration path in this region. Σ_H (not shown here) looks qualitatively similar but decreases faster than Σ_p due to $\sigma_H \propto n_n^2$ and $\sigma_p \propto n_n$ (in the limit of $v_{in}/\omega_{ci} \ll 1$ with the ion gyrofrequency ω_{ci}). The blue areas in Figure 1 (top) represent the approximated Pedersen conductances within each domain in the northern hemisphere in our analytic model and refer to Figure 2. The light blue areas, where the conductance decreases with distance from the moon, are subdivided in eight regions with the radial extent $r_{a,0...8}$ in the equatorial plane. The expression $r_{a,0} = r_s$ indicates Europa's surface, and the region with the extent $r_{a,8}$ represents the area where the conductance nearly vanishes. For a detailed description see Appendix B. The ratio between the conductances Σ_p^n and Σ_p^a shown here is 1:2.

solid surface of the moon anymore (i.e., for $r_\perp > r_s$ with $r_\perp = \sqrt{x^2 + y^2}$). The ionospheric currents couple to the Alfvénic currents at the field lines that are tangent to the moon's solid body. Moving away from the moon, the neutral density of the atmosphere decreases and hence the ionospheric conductances. In the area of the two peaks (see Figure 1) the field-aligned currents are maximum. Therefore, steep gradients in the magnetic field and velocity are expected along field lines crossing this region. An asymmetric atmosphere, e.g., due to an atmospheric inhomogeneity such as a plume, would generate additional rotational discontinuities in the magnetic field at the Alfvénic flux tubes. This means that there is a magnetic jump across the flux tubes but the density is the same on both sides of it. Our analytic model includes both steep gradients due to the global atmosphere and hemisphere coupling currents due to an atmospheric inhomogeneity.

Figure 2 shows a sketch of the geometry and the electric current system for the interaction region of the analytic model. A similar modification of the analytic model was also performed by Simon *et al.* [2011] and Simon [2015] for Enceladus. The extended version of the model presented here considers, in addition to a cylindrical plume (domain p), a less dense atmosphere region (domain s and n) and a second region (domain a) where the wing-aligned currents are concentrated. The region a is subdivided into eight subdomains as shown in Figures 1 and 2. This description represents a simplified approximation of the peak of the conductances at the location of field lines tangent to the solid body and a continuously decreasing neutral density and therefore decreasing conductances when moving outward of region a (see light blue area between $r_s < r_\perp < r_{a,8}$ in Figure 1). Within each domain, the ionospheric conductances are spatially constant. The increased conductance within the plume (domain p) compared to the ambient atmosphere (domain s) results in the formation of the Alfvén winglet within the Alfvén wing in the far field. Besides the hemisphere coupling

Figure 2. Sketch of the geometry of the electric current system (red and purple arrows) for the analytic model with a south polar plume with the radial extent r_p . Europa's solid body is displayed as grey area. The extent of Europa's solid body is r_s . The currents driven in the interaction region are partially volume currents and partially surface currents. The ionospheric currents are volume currents shown in the horizontal red arrows. The Alfvénic currents are volume currents for a smoothly varying ionosphere but in our analytic model represented to a number of surface currents shown as vertical red arrows. The thickness of the red arrows represents the different strengths of the currents in each domain. Due to the north-south asymmetry, additional surface currents, which couple the northern and southern hemispheres, are shown as purple arrows. The interaction region is separated in different domains (n , a , e , s , and p) with constant conductances in each domain. Domain p represents the south polar plume, domain n and s represent the global atmosphere in the northern and southern hemispheres, respectively, domain a represents the region where the wing-aligned currents are concentrated, and domain e the region outside Europa's atmosphere where ionospheric conductivities vanish. The different brightnesses in domain a represent the gradual decrease of the conductances away from Europa in order to consider the decrease of the ionospheric density with distance from Europa (see Figure 1). For a detailed description, see text in section 2.2.1 and Appendix B.

effect, the analytic model is also suitable to study the effects of the Alfvén winglet. We calculate the solution for the electric potential and thus for the electric field in each domain for the cases when the plume is located at the south or the north pole. The calculation of the electric potential and the magnetic field in the Alfvén wing and the winglet for our setup is given in Appendix B.

3. Results

We now quantitatively investigate the effects of an atmospheric inhomogeneity on Europa's plasma interaction with the MHD model and the analytic model introduced in the previous section. With the knowledge about the influence of an atmospheric inhomogeneity on the magnetic field, we will afterward compare the results of the analytic and MHD models with the Galileo magnetic field measurements in order to investigate if signatures of atmospheric inhomogeneities are present in the observations. All results are presented in the EPhiO coordinate system.

3.1. Influence of a Local Atmospheric Inhomogeneity on the Global Plasma Interaction

For a first basic study with the MHD approach the atmospheric inhomogeneity is implemented at the south pole of Europa and contains 50% of the total gas content of Europa's atmosphere. A simplified geometry is chosen here with the background magnetic field pointing in the negative z direction. The initial values and atmospheric properties for the MHD simulation runs used here are given in Tables 1 and 2 denoted by "general model I." The induction in a subsurface water ocean is not included in the first step because it would generate additional asymmetries in the plasma interaction and we are interested in understanding the basic influence of the atmospheric inhomogeneity on the plasma interaction.

3.1.1. Magnetic Field and Plasma Velocity

Europa's atmosphere and plume generate plasma flow and magnetic field perturbations, which propagate as Alfvén waves away from Europa. The root cause of these perturbations are elastic collisions between the ions and the neutrals, plus charge exchange and ionization, where the latter two are often referred to as pickup

Table 2. Atmospheric Properties of the Simulation Runs^a

Model Scenario/ Flyby	$n_{A,0}$ (m^{-3})	$n_{ap,0}$ (m^{-3})	H_0 (km)	H_h (km)	H_Θ (deg)	α	θ_{ap} (deg)	ϕ_{ap} (deg)	γ^b [%]
General model I	5×10^{13}	1.9×10^{14}	100	200	15	2	180	180	10
General model I	5×10^{13}	1.64×10^{15}	100	200	15	2	180	180	50
General model I	5×10^{13}	4.92×10^{15}	100	200	15	2	180	180	75
General model II	5×10^{13}	1.64×10^{15}	100	200	15	2	180	180	50
E17	2.0×10^{13}	5.3×10^{14}	100	200	15	2	140	290	50
E25A	1.0×10^{13}	2.6×10^{14}	100	200	15	2	0	0	50
E26	5.0×10^{13}	1.3×10^{15}	100	200	15	1	135	55	50
E26	5.0×10^{13}	1.3×10^{15}	100	200	15	1	125	35	50

^aAdditionally, simulation runs with a radially symmetric atmosphere but without the atmospheric inhomogeneity ($\gamma = 0\%$) were made with the surface number density $n_{A,0}$ presented in this table.

^bThe ratio between the gas content of the atmospheric inhomogeneity and the gas content of the total atmosphere.

(see equation (2)). We take into account both the velocity and the magnetic field for the consideration of the development of the Alfvén wings and winglets (see Figure 3). The formation of the Alfvén wings is clearly visible in the regions with decreasing plasma bulk velocity v and perturbed B_x north and south of Europa in the xz plane in Figures 3a and 3e, respectively. The Alfvén wings are bent back by a constant angle of $\Theta_A \approx 13^\circ$ with respect to the unperturbed background magnetic field displayed in the white dashed lines (see Figures 3a and 3e). The perturbation of the magnetic field is correlated with the perturbation of the velocity field and can be related through $\delta \underline{B} = \pm \sqrt{\mu_0 \rho_0} \delta \underline{v}$ in the northern (+ sign) and southern (− sign) Alfvén wing [Neubauer, 1980]. The magnetic field components are primarily perturbed in the negative (positive) x direction in the northern (southern) wing (see Figure 3e) and the velocity components in the negative x direction in both wings. Evident in Figures 3a and 3e is the pronounced north-south asymmetry due to the formation of the Alfvén winglet in the southern Alfvén wing. A dense atmospheric inhomogeneity leads to locally enhanced collisional and ionization processes and stronger perturbations within the interaction region. The local atmospheric inhomogeneity at the surface is much denser by a factor of ~ 30 compared to the ambient atmosphere for the results shown here. The enhanced local perturbations are the main cause for the development of an additional, smaller Alfvén wing within the main southern Alfvén wing. Succinctly speaking, the Alfvén winglet is the result of the plasma interaction with an atmospheric inhomogeneity within a global atmosphere, located within the main Alfvén wing. It possesses the same basic properties as the Alfvén wing, i.e., the same bend back and the $\delta \underline{B} = \pm \sqrt{\mu_0 \rho_0} \delta \underline{v}$ correlations. The atmospheric inhomogeneity at the south pole modifies the southern Alfvén wing but only weakly changes the main overall structure. The Alfvén angle is independent of the atmospheric asymmetry.

Figures 3b and 3c show that the plasma flow is diverted around and accelerated up to $|v_\perp| = \sqrt{v_x^2 + v_y^2} \approx 140$ km/s at the flanks of the Alfvén wings (outside the white dashed outer circle). The $\underline{j} \times \underline{B}$ force slows the plasma velocity upstream and reaccelerates it downstream of the wings. In the ionosphere the $\underline{j} \times \underline{B}$ force is predominantly in equilibrium with the forces related to the ion-neutral collisions, electron impact ionization, and charge exchange, while in the Alfvén wings the $\underline{j} \times \underline{B}$ force is in equilibrium with the plasma inertia ($\rho \underline{v} \cdot \nabla \underline{v}$). A result of the interaction is that most of the plasma flow into the ionosphere is reduced and is swept around the moon and the wings.

In the center of the southern Alfvén wing the plasma flow experiences a second shielding as clearly visible in Figure 3b. We introduce the factor $\bar{\alpha} = 1 - \alpha_{\text{plasma}}$ (see equations (A13) and (A14)) which is a measure for the relative strength of the sub-Alfvénic interaction (see also Saur *et al.* [2013]). When the plasma interaction is saturated, the maximum value of $\bar{\alpha} = 1$ is reached and $\bar{\alpha} = 0$ when no interaction takes place. The interaction strength in the winglet is much higher ($\bar{\alpha} \approx 0.95$) than in the surrounding Alfvén wing ($\bar{\alpha} \approx 0.4$). The radius of the winglet depends on the horizontal extent of the surface neutral number density of the inhomogeneity. In the results shown here the extent of the inhomogeneity is $\sim 0.5 R_E$. Within the winglet the magnitude of the perpendicular velocity is reduced to ~ 5 km/s (see Figure 3b) and the magnitude of the perpendicular magnetic field $|B_\perp| = \sqrt{B_x^2 + B_y^2}$ is perturbed by ~ 120 nT (see Figure 3f). At the flanks of the Alfvén winglet the plasma flow is slightly accelerated by $\sim 9\%$ (outside the white dashed inner circle in Figure 3b). Alfvén waves

Figure 3. (a) Plasma bulk velocity in the xz plane ($y = 0 R_E$) calculated with the MHD model. (b, c) Plasma flow velocity field in a cut at $z = \pm 3 R_E$ through the southern and northern Alfvén wings, respectively, in the xy plane. The color scale represents the magnitude of the plasma velocity perpendicular to the magnetic field. (d) Magnitude of the magnetic field in nT in the xz plane ($y = 0 R_E$) calculated with the MHD model. (e) B_x in nT in the xz plane ($y = 0 R_E$). (f) Magnetic field in a cut through the southern Alfvén wing ($z = -3 R_E$) in the xy plane. The color scale represents the magnitude of the magnetic field perpendicular to the background magnetic field. The Alfvén characteristics are shown as white dashed lines in Figures 3a and 3e. The white outer circle indicates the projection of Europa's surface and the white inner circle the projection of the south polar atmospheric inhomogeneity into the southern Alfvén wing in Figures 3b, 3c, and 3f. The white vertical dotted line shows the trajectory along which the magnetic field is displayed in Figure 6. The arrows show the orientation of the plasma flow (Figures 3b and 3c) and magnetic field (Figures 3d–3f), and their lengths linearly scale with highest magnitude of this plane: 145 km/s (Figure 3b), 141 km/s (Figure 3c), 679 nT (Figure 3d), 262 nT (Figure 3e), and 121 nT (Figure 3f).

Figure 4. Plasma number density in cm^{-3} in the xz plane ($y = 0 R_E$) calculated with the MHD model.

associated with the inhomogeneity at the south pole can not propagate into the northern hemisphere along field lines intersecting the moon. No local perturbations within the northern wing are recognizable as a direct consequence of the inhomogeneity (see Figure 3c).

A basic property of the wings is that the magnitude of the magnetic field is constant inside the Alfvén wings [Neubauer, 1980], also visible in the far field in our results in Figure 3d. The fast mode generated by the interaction upstream of the moon propagates in all directions. The amplitude of the fast magnetosonic mode perturbations decreases as a function of distance from Europa and can be neglected a few R_E away from Europa. The propagation of the fast mode is associated with a compression and bending of the magnetic field lines. The compression of the field lines upstream of Europa leads to a pileup and thus to an enhancement of the magnitude of the magnetic field. This increase of the magnitude of ~ 100 nT is visible in Figure 3d. It is also visible that a second pileup region develops at the south pole associated with the inhomogeneity. This region is more distinctive than the large-scale upstream region and the perturbed magnitude of the magnetic field increases up to ~ 700 nT.

Figure 3a shows structures especially in the northern but also southern hemisphere in the plasma velocity going from the poles downstream of the moon by an angle of about 50° to the axis (on the northern hemisphere). These perturbations require a more detailed study but might develop in our simulations due to density and pressure gradients within the Alfvén wing related to the compressional slow mode also observable in the plasma number density in Figure 4.

In summary, our simulation shows that due to a local atmospheric inhomogeneity an Alfvén winglet within the large-scale southern Alfvén wing forms. In the winglet the magnetic field and the velocity experience a stronger perturbation compared to the perturbations in the main wing due to the dense atmospheric inhomogeneity.

3.1.2. Plasma Density

In Figure 4 we display the plasma number density in the xz plane. As magnetospheric electrons flow past the atmosphere and convect through it, the neutral particles in the atmosphere are ionized and the plasma density upstream of the moon increases. The ionized plasma gets picked up and moves downstream. Europa's ionosphere is therefore not an ionosphere in chemical equilibrium, i.e., where production and recombination differ strongly. At Europa, production and convection determine the ionospheric mass balance. Most of the plasma is concentrated at the region of the local inhomogeneity with densities up to $\sim 1 \times 10^5 \text{ cm}^{-3}$. Farther away from the moon the density decreases to its ambient value. No significant perturbation of the plasma density is expected in the Alfvénic far field. Downstream of the moon, recombination but no ionization takes place. Since the ionospheric particles which impinge Europa's surface are absorbed, a wake downstream of the moon forms where the plasma density is strongly decreased. Compressional slow mode perturbations act downstream of the moon to reestablish pressure equilibrium. The increased density structure at the northern hemisphere in Figure 4 might be attributed to a combination of convection of plasma and of slow mode perturbations which propagate with a local sound speed velocity of ~ 30 km/s.

Figure 5. (a) Alfvénic current $j_{c_A}^+$ in A/m² in a cut through the southern Alfvén wing in a plane perpendicular to the southern Alfvén characteristic at $z = -3 R_E$. (b) Alfvénic current $j_{c_A}^-$ in A/m² in a cut through the northern Alfvén wing in a plane perpendicular to the northern Alfvén characteristic at $z = 3 R_E$. In the wing coordinate system, the z_{W+} (z_{W-}) axis is parallel to the southern (northern) Alfvén characteristic, the y_{W+} axis is the same as in the EPhiO system and the $x_{W\pm}$ axis completes the right-handed coordinate system. The white outer circle indicates the projection of Europa's surface and the white inner circle the projection of the south polar atmospheric inhomogeneity into the southern Alfvén wing.

3.1.3. Electric Currents in the Alfvén Wings

Collisions, charge exchange, and electron impact ionization modify the plasma flow and thus generate magnetic field perturbations and associated electric currents. The ionospheric electric currents are determined by the local ionospheric conductivities and electric field. Farther away from Europa, the ionospheric conductivities vanish and the ionospheric currents are fed into the Alfvén wing currents. The Alfvénic currents $j_{c_A}^{\pm}$ parallel to the wing, i.e., the Alfvén characteristics are displayed in a cross section through the southern and northern Alfvén wings in the plane perpendicular to $\underline{c}_A^{\pm}$ (equation (B11)) at $z = \pm 3 R_E$ in Figures 5a and 5b, respectively. When we only consider a radially symmetric atmosphere, we expect $j_{c_A}^{\pm}$ to be concentrated at the flanks of the Alfvén wings as it is shown for $j_{c_A}^-$ in Figure 5b. Due to the local atmospheric inhomogeneity, a pronounced second current system in the southern Alfvén wing arises (see Figure 5a). The inhomogeneity drives a surplus of the ionospheric electric current at the south pole that is closed in the southern far field. The current density is concentrated at the flanks of this Alfvén winglet and the direction of the currents is the same as in the southern Alfvén wing. A fraction of the current associated with the local inhomogeneity is closed in the northern

Figure 6. Magnetic field components in the (a) southern and (b) northern Alfvén wing along a trajectory parallel to the y axis and shifted $0.3 R_E$ downstream from the wing center. Results are calculated with the MHD model. The inhomogeneity is located at the south pole in a radially symmetric atmosphere. The initial values and atmospheric properties can be found in Tables 1 and 2 denoted by “general model I.” The parameter γ denotes the ratio between the mass content of the atmospheric inhomogeneity to the mass content of the total atmosphere. The vertical lines represent the projection of the position of the center of the inhomogeneity into the southern Alfvén wing (dotted green line), the position of the flanks of the Alfvén winglet (dotted red lines), the Alfvén wing crossing (dashed grey line), and the position of the flanks of the Alfvén wings (dashed blue line).

far field through surface currents. For the model scenario shown here we have calculated a total Alfvén wing current through the whole southern Alfvén wing of 4.9×10^5 A and an Alfvénic current through the winglet of 1.8×10^5 A.

3.1.4. Influence of Varying Neutral Density Distribution on the Magnetic Field in the Alfvénic Far Field

As demonstrated in the previous section, the perturbations of the magnetic field in the Alfvén wings are controlled by the neutral atmosphere. Here we show how different atmospheric inhomogeneities affect the perturbations of the magnetic field in the northern and southern Alfvén wings. Figures 6a and 6b show the components of the magnetic field along trajectories parallel to the y axis shifted $0.3 R_E$ downstream from the center of the wing in the southern and northern Alfvén wings, respectively. The hypothetical trajectories are displayed as white vertical lines in Figures 3b, 3c, and 3f. We display the magnetic field on a shifted trajectory away from the center of the wings because on a trajectory through the center some properties of the magnetic field are less significant due to symmetry reasons. The different lines show the magnetic field from the MHD models with a radially symmetric atmosphere (grey line) and different densities of the atmospheric inhomogeneity in the ambient radially symmetric atmosphere. The factor γ indicates the ratio between the total mass of the atmospheric inhomogeneity and the total mass of the global atmosphere. This ratio γ is varied between 0% and 75%.

As expected the perturbations of the magnetic field are symmetric in the northern and southern Alfvén wings for a radially symmetric atmosphere and dominant in the x component due to the bending of the magnetic field lines, as visible in the grey line in Figures 6a and 6b. Within the wings the magnetic field is more perturbed at the inner face of the wings (at $y \approx \pm 0.8 R_E$) with 75 nT than in the center (at $y = 0 R_E$) with a perturbation of 60 nT in the x component. This is a result of the increased conductances on field lines more tangential to Europa, i.e., for regions characterized by $x^2 + y^2 \approx R_E^2$ (see also maximum of conductance near r_s in Figure 1). The magnetic field perturbations are structured similar to the plasma velocity perturbations in the wings. Therefore, the acceleration of the plasma at the flanks of the Alfvén wings results in a local decrease (increase) of B_x in the southern (northern) wing as visible in the grey line at the position of the vertical dashed blue

line in Figures 6a (top) and 6b (top). Due to the diversion of the plasma flow around the Alfvén wing, the magnetic field is perturbed in the y direction at the flanks of the wings. B_z is more perturbed at the inner face of the wings with a perturbation of 9 nT than in the center of the wings with a perturbation of 6 nT shown in the grey line in Figures 6a (bottom) and 6b (bottom). This follows from $|B| = \text{const}$ in the Alfvén wings and the described B_x dependence.

A south polar inhomogeneity in a radially symmetric atmosphere leads to the formation of an Alfvén winglet within the southern wing. At the dense inhomogeneity more perturbations are generated which map out into the southern Alfvén wing as visible in the global maximum in the center of the wing (at the position of the dotted green line) in the B_x component in the magenta, green, and blue lines in Figure 6a (top). The perturbations in all three components become stronger with increasing density of the inhomogeneity. The perturbation in the wing center reaches a value up to ~ 125 nT for $\gamma = 75\%$. The plasma flow within the southern Alfvén wing is directed around the winglet and is accelerated at its flanks (at the position of the vertical dotted red lines) resulting in a decrease of the perturbation of the B_x component. We see that the denser the inhomogeneity, the slower the plasma flow within it and the faster the flow around the flanks of the winglets. Faster flow leads to smaller perturbation in B_x in the surrounded Alfvén wing. Farther away from the projection of the center of the inhomogeneity (at the position of the vertical dashed grey lines) the influence of the Alfvén winglet decreases and the effect of the Alfvén wing becomes visible in the increase of B_x (see Figure 6a, top). The diversion of the plasma flow becomes also more effective with increasing density of the inhomogeneity. Therefore, the perturbation of B_y around the winglet becomes stronger as evident in the minimum and maximum at the position of the vertical dotted red line in Figure 6a (middle). For example, a plume at Europa that contains 50% of the total mass content of the atmosphere can exhibit a perturbation in the y direction of ~ 25 nT. The behavior of the magnetic field in the northern Alfvén wing is very similar in all four cases (see Figure 6b). Here B_y and B_z are weakly disturbed. In the northern hemisphere the atmosphere is homogeneous, and therefore, no local perturbations within the northern wing develop on smaller scales in contrast to the southern wing.

3.2. Comparison Between Analytic Model and MHD Model Results

In Figures 7a and 7b we display the calculated magnetic field in the northern and southern Alfvén wings on a trajectory along the y direction shifted by $0.3 R_E$ downstream from the center of the wings. The red lines show the analytic model results calculated with a south polar atmospheric inhomogeneity. Additionally, we compare these results with MHD model results calculated with an inhomogeneity which contains 50% of the total gas content of Europa's atmosphere displayed in the green lines. For the analytic model, we chose values for the conductances which fit the MHD model data.

Within the plume indicated by p in Figure 7a the magnetic field experiences the maximum perturbation in B_x direction. At the boundaries of the plume to the global atmosphere indicated with s , a magnetic field discontinuity arises in the analytic model results (red lines). This discontinuity is a model discontinuity because the real plume density does not abruptly jump but its transitions are smoothly to the global atmospheric density. Inside the southern Alfvén wing (domain s) the B_x component is still perturbed in the positive x direction due to the bending of the wing. At the boundary between outside ($r > R_E$) and inside the Alfvén wing ($r < R_E$) indicated with a and s , respectively, a jump of the magnetic field components can be observed. The jump is a result of the peak of the Pedersen conductance in Europa's atmosphere and the effect of the hemisphere coupling currents. The part of the discontinuity due to the hemisphere coupling is a real physical discontinuity. This transition region is located between the volume currents which are fed into the southern atmosphere and the surface currents which connect both hemispheres. The volume and surface currents have opposite directions (see also Figure 2) and therefore produce the magnetic field signatures in the transition region a to s shown as red lines in Figure 7a. Outside the Alfvén wing (domain a) the ionospheric conductance gradually decreases and so do the magnetic field perturbations. In the region where the ionospheric conductance vanishes (domain e) the magnetic field components return to their upstream conditions. On the northern hemisphere there is no inhomogeneity in the atmosphere; therefore, the magnetic field in the northern Alfvén wing (Figure 7b) only experiences perturbations which occur from the interaction with a global atmosphere except in the transition region between n and a . The hemisphere coupling effect also generates discontinuities in the northern Alfvén wing as visible in the magnetic field components in the red lines in Figure 7b between n and a .

Figure 7. Magnetic field components in the (a) southern and (b) northern Alfvén wing along a trajectory parallel to the y axis and shifted $0.3 R_E$ downstream from the wing center. The green lines show the solution with a south polar atmospheric inhomogeneity ($\gamma = 50\%$) calculated with the MHD model. The red lines indicate the Alfvénic perturbation for a nonsymmetric interaction with an atmospheric inhomogeneity at the south pole with $r_s = 1 R_E$, $r_p = 0.5 R_E$, $\Sigma_p^s = \Sigma_p^n = 1 S$, $\Sigma_p^p = 15 S$, $\Sigma_p^a = 6 S$ calculated with the analytic model. The ionospheric Hall effect was neglected with $\Sigma_H^s = \Sigma_H^n = \Sigma_H^p = \Sigma_H^a = 0 S$. The values were chosen to fit the MHD model results (green lines). The other quantities for the calculation of the magnetic field perturbation can be found in Table 1 denoted by “general model I.” The red lines show a stepwise behavior due to the sharp boundaries between each domain. The vertical dashed lines represent the boundaries between the domains a , n , s , and p referring to Figure 2. The wavelike structure of the green lines in B_z is a pure numerical effect.

Europa’s global atmosphere weakens the effect of the hemisphere coupling currents. This effect is very small compared with the effect generated by the global atmosphere which occurs due to the peak of the ionospheric conductances. We calculated a jump of about 5% of the global perturbation in the magnetic field components associated with the hemispheric coupling currents for the approach used here. Consequently, an observed large jump of the magnetic field over a short but still sufficiently finite length scale during an Alfvén wing crossing at Europa is most likely a steep gradient due to the atmospheric effect and a discontinuity due to an asymmetric atmosphere would be hardly detectable in the data set (see further discussion in section 3.4.1).

The analytic model results provide information on the influence of the hemisphere coupling due to the inhomogeneity and the atmospheric effect due to the peak of the ionospheric conductances at the flux tube boundary. The comparison between the analytic and MHD model shows that the results are in general agreement with each other except for the discontinuities. The transition regions calculated with the MHD model (green lines) are much smoother in comparison with the analytic model results for two reasons:

1. A more realistic smoother neutral atmosphere.
2. Remaining small discontinuities from the hemispheric coupling currents are smeared out due to the finite resistivity and viscosity of the MHD codes.

The maximum perturbation in B_x direction in the Alfvén winglet (domain p in Figure 7a, top) is larger in the MHD model results than in the analytic model results, because the conductance calculated with the MHD model in domain p reaches its maximum in the center of the inhomogeneity while the conductance given in the analytic model is constant in this domain. The B_z component also experiences stronger perturbations with a decrease in magnitude to ensure the required constancy of the magnetic field magnitude in the northern and southern Alfvén wings and winglet (see Figures 7a (bottom) and 7b (bottom)). Due to the diversion of the plasma flow around the Alfvén winglet, the B_y component is perturbed in the negative and positive y direction around the winglet in the ambient Alfvén wing (see red and green lines in Figure 7a, middle). In the northern Alfvén wing (domain n in Figure 7b) the B_y component calculated with the MHD model is slightly perturbed (~ 3 nT) while the B_y component calculated with the analytic model does not experience any perturbation due to the constancy of the conductance inside domain n .

Figure 8. Plasma flow velocity field in a cut through the southern Alfvén wing ($z = -3 R_E$) in the xy plane for plasma interaction (a) without and (b) with induction in a subsurface water ocean. The magnitude of the plasma velocity perpendicular to $\underline{B}_0$ is color coded. The white circle indicates the projection of Europa's surface into the southern Alfvén wing. The lengths of the arrows linearly scale with the highest magnitude of this plane: 144 km/s (Figure 8a), 151 km/s (Figure 8b).

3.3. Influence of Induced Fields on the Alfvén Winglet

A spatially homogeneous inducing field in a radially symmetric ocean induces a dipole field. Deviations from these idealized conditions of the inducing field and the conductive regions will result in higher-order multipole fields [see, e.g., Schilling *et al.*, 2004, 2007]. The induced magnetic field directly modifies the magnetic field in the surrounding of the moon. However, it also affects the far field through a shrinkage and a displacement of the Alfvén wings [Neubauer, 1999]. The inducing field is strongest when Jupiter's dipole moment points toward or away from Europa. In this section we study the case when Europa is located north of the magnetic equator ($\lambda_{III} = 200^\circ$). In this case the induced dipole moment points mainly toward the Jupiter-facing side at the position of Europa. The setup of the plasma conditions for the MHD simulation used here are given in Tables 1 and 2 denoted by “general model II.” In Figure 8b we display the perpendicular plasma velocity in a cross section through the southern wing when induction is included and compare it to the case without induction in Figure 8a. The background magnetic field has a strong y component and therefore the Alfvén wings are additionally tilted in the y direction (see also Figure 7A in Neubauer [1999]). The consequence of the y tilt of the large Alfvén wing is that the Alfvén winglet sitting exactly at the south pole is not in the center of the large wing anymore. The winglet is shifted to the Jupiter-facing side as visible within the white dashed

Figure 9. Trajectories of the Galileo flybys E17 (black line), E25A (blue line), and E26 (red line) in the EPhiO coordinate system. The times associated with the spacecraft's positions are labeled on the trajectories. The green crosses mark the position of the closest approach.

Table 3. Properties of the Europa Flybys E17, E25A, and E26

Flyby	Date, Time ^a (UTC)	Altitude (km)	TA ^b (deg)	Mag. Lat. (deg)	λ_{III} (deg)
E17	1998/9/26, 03:53:52	3581	293.9	4.6	140
E25A	1999/11/25, 16:29:00	8648	187.2	9.5	200
E26	2000/1/3, 17:59:37	340	216.4	-7.8	346

^aAt the closest approach CA. Dates are formatted as year/month/day.^bTrue anomaly.

circle representing the projection of Europa's surface into the wing in Figure 8. To quantify the relative importance of the induced fields compared with the background magnetic field *Neubauer* [1999] introduced the inclination angle of the Jovian magnetic field with respect to the Jovian equator at the location of the moon [see *Neubauer*, 1999, equation (5)]. For the scenario shown here the inclination angle is 65° . Therefore, we expect a small distortion of the cross section of the Alfvén wings by less than 10% according to Figure 5 in *Neubauer* [1999]. Comparing the results with and without induction (see Figure 8), a small displacement to the anti-Jupiter-facing side and a distortion along the x direction of the winglet can be observed. Moreover, the results of the plasma interaction plus induced fields in a subsurface ocean show that the acceleration of the plasma at the flanks of the Alfvén wings and the winglet is more distinctive than it is the case without induction. This is a result of the small displacement of the winglet and its flanks to the negative y direction and the nonconstant behavior of the velocity within the Alfvén wing.

3.4. Modeling of the Galileo Flyby Scenarios

Now we study the influence of an inhomogeneity by comparing our simulation and analytic results with the Galileo MAG data along trajectories of three different flybys: E17, E25A, and E26. The flyby trajectories are displayed in Figure 9 with associated properties of the flybys summarized in Table 3. Since the Alfvénic far field is diagnostic of Europa's atmospheric properties, a strong local atmospheric inhomogeneity should be detectable in the magnetic field perturbations in the Alfvén wing. Among the 12 Europa flybys, only the three flybys studied here crossed the Alfvén wings. Our aim is to investigate whether signatures of atmospheric inhomogeneities are present in the measured data and whether we can draw conclusions on the existence of an inhomogeneity in the atmosphere only from magnetic field data. The initial values and atmospheric properties of the flybys used in the MHD model are presented in Tables 1 and 2. Induction in a subsurface water ocean is included in the associated MHD simulations.

3.4.1. Europa Flyby E17

The flyby E17 occurred in the high plasma density region near the center of the Jovian plasma sheet at an altitude of ~ 3600 km. Galileo passed downstream through the southern Alfvén wing. The data (black line) in Figure 10 shows a strong perturbation of the magnetic field in the positive x direction due to the bending of the magnetic field lines and weak perturbations in the B_y and B_z components. Furthermore, small-scale fluctuations on top of the main perturbations are measured and could be due to kinetic effects but are not subject of this paper.

The analytic model results with a symmetric atmosphere (see blue line in Figure 10a) are in good agreement with the overall data structure. A local atmospheric inhomogeneity in the southern hemisphere (see red line in Figure 10a) would generate perturbations that are not seen in the data during this flyby. For the radius r_s of the region where the field lines are tangent to Europa we chose a value of $0.9 R_E$ because it better fits the extent of the crossing of the Alfvén wing, but it does not qualitatively change the form and the amplitude of the perturbation. The smaller extent of the interaction region could be an effect of the induced magnetic field. *Volwerk et al.* [2007] estimated a shrinkage of 0.96 and an offset of $0.1 R_E$ of the Alfvén wing during E17.

The MHD model results confirm the picture that we have from the analytic model (see Figure 10b). The results from the model with the radially symmetric atmosphere (blue line) fit the overall structure very well. The model results with a local inhomogeneity in the atmosphere (red line) show that the magnetic field would experience a local perturbation in the negative x and y directions that we do not see in the measured data. The B_z component is slightly overestimated by our MHD model compared to the measured data. The magnitude of the B_z component in the MHD model results without inhomogeneity is reduced up to 45 nT in order to maintain the constancy of the magnitude of the magnetic field in the Alfvén wing.

Figure 10. Magnetic field components along the E17 flyby trajectory in the EPHIO coordinate system. (a) Comparison between the Galileo MAG data (black lines) and the results obtained from the analytic model where a south polar inhomogeneity in a global atmosphere (red lines) with $r_s = 0.9 R_E$, $r_p = 0.7 R_E$, $\Sigma_p^s = \Sigma_p^p = 3 S$, $\Sigma_p^p = 15 S$, $\Sigma_p^a = 6 S$, $\Sigma_H^p = \Sigma_H^s = \Sigma_H^n = \Sigma_H^a = 0 S$ is considered. The values were chosen to fit the measured data (black lines). The other quantities for the calculation of the magnetic field perturbation can be found in Table 1. The blue lines show the analytic results for a homogeneous atmosphere. (b) Comparison between the MAG data (black lines) and the results obtained from the MHD model where a radially symmetric atmosphere (blue lines) is considered. The red lines show the model results with an inhomogeneity at $\phi = 290^\circ$ and $\theta = 140^\circ$ in a radially symmetric atmosphere. The dashed vertical line displays the closest approach at 03:54 UT, $x = 1.57 R_E$, $y = -1.85 R_E$, and $z = -2.23 R_E$.

The perturbations in the analytic and MHD model due to the atmospheric inhomogeneity (see red lines in Figures 10a and 10b) are slightly different because the location of the inhomogeneity differ between both models. In the analytic model used here, we only have the opportunity to place the center of the inhomogeneity exactly at the north or south pole and vary the extent.

In the time interval before the Galileo spacecraft enters the Alfvén wing at 03:56 UT the measured B_x component shows a decrease which is associated with the Alfvén wing currents. This decrease is followed by a steep gradient in the positive x direction at the entry of the Alfvén wing. This may be explained by the fact that Galileo entered the Alfvén wing at the location of maximum current [Volwerk et al., 2007]. The steep gradient is measured over four data points with a resolution of 6 s per data point implying a distance of 176 km.

Our model can explain this steep gradient. The ionospheric conductances given by equation (17) peak at the location with field lines tangent to Europa because of the change of the integration path length. Moving outward from Europa, the conductances decrease since the neutral gas density falls off and therefore collisions between magnetospheric particles and neutrals decrease. The region of the decrease is strongly dependent on the atmospheric and ionospheric scale heights. Assuming an effective scale height for the ionospheric Pedersen conductivity of $\tilde{H} = 90$ km in the analytic model (with an atmospheric scale height $H_a = 145$ km and plasma scale height $H_e = 240$ km, see equation (B6)) leads to a steep gradient in the conductances and thus also to a steep gradient in the magnetic field. The gradients are consistent with the measured magnetic field data. An effective scale height larger than 90 km results in a decrease of the steepness of the gradient and does not fit the measured data very well anymore. The atmospheric and plasma scale heights are variable with the distance from Europa because they are influenced by heating and cooling of the atmosphere and ionization, recombination and transport processes in the ionosphere. The variability of the scale height could be an explanation for the perturbation structure in B_x seen in the observed data between 03:50 UT and 03:56 UT.

Figure 11. Magnetic field components along the E25A flyby trajectory in the EPHIO coordinate system. (a) Comparison between the Galileo MAG data (black lines) and the results obtained from the analytic model where a north polar inhomogeneity in a global atmosphere (red lines) with $r_s = 1 R_E$, $r_p = 0.8 R_E$, $\Sigma_p^s = \Sigma_p^n = 1.5 S$, $\Sigma_p^p = 4 S$, $\Sigma_H^p = 2 S$, $\Sigma_H^s = 3.5 S$, $\Sigma_H^n = \Sigma_H^a = 0 S$ is considered. For further information, see Figure 10. (b) Comparison between the Galileo MAG data (black lines) and the results obtained from the MHD model where a radially symmetric atmosphere (blue lines) is considered. The red lines show the model results with an inhomogeneity at the north pole ($\theta = 0^\circ$) in the radially symmetric atmosphere. The dashed vertical line displays the closest approach at 16:29 UT, $x = 3.04 R_E$, $y = -0.23 R_E$, and $z = 5.79 R_E$.

We can not rule out that the steep gradient still contains a contribution due to a strongly asymmetric atmosphere, e.g., due to a plume in the northern hemisphere or on the upstream side of the southern hemisphere, since the jumps in the magnetic field data coincide with the location of the hemisphere coupling currents. As we already discussed in section 3.2, it is difficult to separate between the atmospheric effect (i.e., the jump in the vertical column density through a radially symmetric atmosphere at the limb of the moon) and the hemisphere coupling effect in the jump of the magnetic field. High time resolution data would therefore help to further disentangle these effects.

3.4.2. Europa Flyby E25A

The flyby E25A occurred at a large distance of $\sim 5.5 R_E$ when Europa was located outside the plasma sheet. Galileo passed downstream through the northern Alfvén wing nearly radially toward Jupiter. The resolution is low compared to the other flybys with ~ 140 km between two data points and therefore insufficient to resolve the high-frequency perturbations or steep gradients due to hemisphere coupling currents if a strongly asymmetric atmosphere existed at that time. Since the flyby occurred in the Alfvénic far field of the moon, it is not influenced by the effects of the ionospheric currents and therefore particularly well suited for the application of the analytic model. The measured data (black line) presented in Figure 11 shows a perturbation of the magnetic field in the negative x direction due to the bending of the magnetic field lines in the northern Alfvén wing. The magnetic field signatures are better reproduced by our analytic model (see Figure 11a) when a local inhomogeneity is included in the northern hemisphere in a global radially symmetric atmosphere (red line). The atmospheric inhomogeneity is located at the north pole and has a radial extent of about $0.8 R_E$. The conductance of the inhomogeneity ($\Sigma_p^p = 4 S$) at this location is more than twice as large as the conductance of the global atmosphere ($\Sigma_p^n = 1.5 S$). The values of the magnetic field along the trajectory indicate that the enhancement of the atmospheric density in the area of the inhomogeneity is not that significant as it is, e.g., for an inhomogeneity with $\gamma = 50\%$ and $\Sigma_p^p = 15 S$ as presented in Figure 7a. The contribution of the denser north polar inhomogeneity and especially the ionospheric Hall effect generate the local perturbation of ~ 20 nT in B_y at 16:38 UT in our analytic model. Also, the direction of the perturbation of the B_z component is consistent with the observed data.

Figure 12. Magnetic field components along the E26 flyby trajectory in the EPHIO coordinate system. Comparison between the Galileo MAG data (black lines) with the results from the MHD model where a radially symmetric atmosphere (blue lines) and different locations of the atmospheric inhomogeneities are considered. The magenta lines show the results with an inhomogeneity at $\phi = 35^\circ$ and $\theta = 125^\circ$ and the green lines with one at $\phi = 55^\circ$ and $\theta = 135^\circ$. The dashed vertical line displays the closest approach at 17:59 UT, $x = -0.83 R_E$, $y = 0.04 R_E$, and $z = -0.89 R_E$.

Figure 11b shows the results from our MHD model with a radially symmetric atmosphere (blue line) and results with a local inhomogeneity at the north pole in a radially symmetric atmosphere (red line). We do not have the ionospheric Hall effect included in the MHD model so that we can not confirm the significant influence of the Hall effect in the atmospheric inhomogeneity that we see in the results of the analytic model. Both results fit the global structure of the data and an atmospheric inhomogeneity is not indicated.

Although the analytic model results indicate the possibility of a local inhomogeneity in the northern hemisphere, it is not possible to draw clear conclusions on the existence of an inhomogeneity during this flyby. Other reasons causing the observed magnetic field signature could be perturbations of Jupiter's magnetosphere or small-scale dynamic plasma processes. Additionally, there are other magnetic field substructures along the flyby which are not explained by our analytic model.

3.4.3. Europa Flyby E26

The E26 flyby was a south polar pass, upstream of the moon, and almost radially toward Jupiter. Europa was located south of Jupiter's magnetic equator in a low plasma density environment. The signals from induced magnetic fields are particularly strong during this flyby. This pass occurred very close to the moon with a closest approach altitude of ~ 340 km. The analytic model is not applicable here because at this altitude the interaction is not purely Alfvénic, and additionally to the Alfvénic currents, ionospheric currents also modify the magnetic field environment. The black line in Figure 12 shows the measured data during E26. The perturbations in the B_x component in the interaction region are similar to the perturbations during the E17 flyby. The B_x component is affected by the bendback of the southern Alfvén wing resulting in a slight decrease shortly before the Alfvén wing entry at 17:59 UT and a global enhancement of B_x during the Alfvén wing crossing. The rotation of B_y and B_z is the result of the influence of the induced magnetic field and the ionospheric currents. The B_x component shows a strong gradient with an increase from -14 nT to 150 nT during the Alfvén wing entry similar to the E17 data. The strong increase of the B_x component takes place over 19 s (57 data points), which corresponds to a length scale of 152 km of the moving spacecraft. Inside the interaction region all three magnetic field components show a very disturbed structure. Outside of the interaction region the data show a smooth trend indicating a fairly quiet magnetic field environment during this flyby.

Figure 13. Magnetic field components in the xy plane at $z = -0.89 R_E$ for three different MHD model runs (see Figure 12) with a radially symmetric atmosphere (a) and additional atmospheric inhomogeneity at different locations (b and c) during the E26 flyby. The dashed white line shows the trajectory of E26.

The MHD model that results from a simulation with a radially symmetric atmosphere (blue line in Figure 12) fit the overall signature very well similar to the results of *Schilling et al.* [2007] and *Rubin et al.* [2015]. A prominent double-peak structure is evident in the measured B_x component. Neither *Schilling et al.* [2007] nor *Rubin et al.* [2015] could fit this double-peak signature with a global atmosphere. When we include a dense inhomogeneity on the southern hemisphere (longitude $\phi = 35^\circ$ and colatitude $\theta = 125^\circ$) within the atmosphere, our model is able to produce a double-peak structure in B_x but width and amplitude differ compared to the observations (see magenta line in Figure 12). The first peak in our model is a result of the maximum of B_x that occurs in the southern main wing, and the second peak is a result of the maximum in the southern Alfvén winglet. The ionospheric closure currents increase the effect of the atmospheric inhomogeneity. The B_y component of the model with an atmospheric inhomogeneity is also perturbed on smaller scales compared to the model with a radially symmetric atmosphere. By shifting the location of the inhomogeneity more to the upstream side at the longitude $\phi = 55^\circ$ and colatitude $\theta = 135^\circ$ (green line), the double-peak structure changes. The B_y component provides a better fit to the data but the perturbation of the B_z component in the MHD model is not in agreement with the measured perturbation. Hence, the exact magnetic field signature is very sensitive to the location of the prescribed atmospheric inhomogeneity. The modifications of the magnetic field due to the variation of the location of the atmospheric inhomogeneity is shown in Figure 13. It displays the magnetic field components in the xy plane at the altitude $z = -0.89 R_E$ for the three different cases discussed in Figure 12. The inhomogeneity generates an area of enhanced B_x and B_z in this plane

(see Figures 13b, top, 13b, bottom, 13c, top, and 13c, bottom). B_y is influenced by the induced field at this altitude (see Figure 13a, middle). The inhomogeneity modifies the plasma flow and thus also the resultant magnetic perturbations and associated electric currents. Both the induced fields and the magnetic field perturbation contribute to the structure in B_y seen in Figures 13b (middle) and 13c (middle).

Although the model is not able to reproduce the exact structure of the magnetic field perturbations during this flyby, it suggests that a dense and localized inhomogeneity in the atmosphere could perturb the magnetic field on smaller scales with a similar orientation like the observed perturbations. The large number of possibilities to describe such an inhomogeneity with the free parameters like the latitudinal extent, density, scale height and position and also the number of inhomogeneities makes it difficult to find the best fit parameters for the data. During the flyby, Europa was at an orbital true anomaly of 216° similar to the true anomaly during the December 2012 HST observations when the plume was identified. Tensile stresses on polar fractures and fractures around the leading and trailing meridians are expected to be highest when Europa is located in the apocenter of its orbit [Roth *et al.*, 2014b]. The plumes that are included in our model are located in the southern hemisphere between the equator and the south pole and between the sub-Jovian and the leading side. Therefore, a clear correlation between the stresses for a certain true anomaly and the possible occurrence of atmospheric inhomogeneities is not given here.

It is also possible that other effects play a role in the modification of the magnetic field that we have not included in our MHD model such as the ionospheric Hall effect, solar illumination, or day-night asymmetry. Plainaki *et al.* [2013] demonstrate that the spatial distribution of Europa's atmosphere depends on the time-varying relative orientations of solar illumination and the incident plasma direction. Their study suggests an increase in the atmospheric density by a factor of ~ 4 depending on the configuration between the Sun and Europa. But their model does not produce sharp gradients in the neutral density. Solar illumination, according to their model, would produce a more global asymmetry which would appear not to be the reason for the generation of such an inhomogeneous localized structure in the magnetic field components. But further modeling of Europa's atmosphere is required to better understand the real spatial structure of its atmosphere. Besides the atmospheric and ionospheric effects, sudden magnetospheric effects (e.g., flux tube interchange, pressure balanced structures) during the time of the flyby could also affect the observed magnetic field. Therefore, the magnetic field data needs to be interpreted with caution and it is not possible to derive a rigorous conclusion about an atmospheric inhomogeneity during this flyby. Velocity and plasma pressure data, if available, would be very helpful for the interpretation of the plasma interaction. The analysis of plasma data would serve to separate between Alfvénic and magnetospheric effects, e.g., pressure balanced structures during the flyby. An asymmetric atmosphere, e.g., due to the plumes, is expected to produce Alfvénic perturbations, which are visible in the velocity and magnetic field data in the far field in a distinctly correlated way. Magnetospheric perturbations would be present in the magnetic field, density, and plasma pressure data in a different way.

4. Summary and Discussion

We present a study of the influence of inhomogeneities in Europa's atmosphere, such as plumes, on the interaction between the corotating magnetospheric plasma and Europa's atmosphere. We apply two different approaches, a 3-D MHD and an analytic approach, to model this interaction. The MHD model considers self-consistently physical processes of the plasma interaction and includes plasma production, loss, and induction in a subsurface ocean. The analytic approach to describe the effects of a local inhomogeneity is based on the model for sub-Alfvénic nonsymmetric interaction by Saur *et al.* [2007] which we expand and solve for conditions adopted to Europa. The analytic calculations support the MHD model results and provide additional insight into the influence of local inhomogeneities when embedded in a global atmosphere, e.g., the ionospheric Hall effect and discontinuities associated with the hemisphere coupling due to a strong asymmetric atmosphere.

By applying these models we demonstrate that atmospheric inhomogeneities do not only have a large effect on the plasma and magnetic field environment near Europa but also affect the Alfvén wings in the far field. Our study shows that an inhomogeneity in the atmosphere causes a pronounced north-south asymmetry in the Alfvén wings and the development of an Alfvén winglet within the Alfvén wing which is connected to the hemisphere with the inhomogeneity. Our MHD model results show that in the presence of a global atmosphere with a surface density of $\sim 5 \times 10^{13} \text{ m}^{-3}$ and a plume with a surface density of $\sim 1.6 \times 10^{15} \text{ m}^{-3}$,

a height of 200 km, and a latitudinal extent of 15° , the plasma velocity experiences a decrease up to 95% of the upstream velocity in the Alfvén winglet and a decrease up to 60% of the upstream velocity in the ambient Alfvén wing. The magnetic field perturbations are stronger in the Alfvén winglet with up to 120 nT than in the ambient southern Alfvén wing with 40 nT in the positive x direction. The global form of the Alfvén wings does not change since the Alfvén velocity in the far field is unaffected by the distribution of the neutral density in the atmosphere.

According to our analytic model results, Europa's global atmosphere weakens the effect of the hemisphere coupling and generates steep gradients in the magnetic field. Unlike Enceladus, which lacks a global atmosphere and where the plasma interaction is driven by the plumes, Europa's global atmosphere has a huge effect on the plasma interaction. Our analytic model results show that the resultant discontinuities for a plume that contains 50% of the mass content of Europa's atmosphere would only contribute with $\sim 5\%$ to magnetic field amplitudes generated by the global atmosphere. Within the temporal resolution of the available data, such a discontinuity is difficult to detect given the additional steep gradients due to the global atmosphere.

Additionally, we investigate if signatures of atmospheric inhomogeneities are locally detectable and visible in magnetic field measurements of the Galileo Magnetometer. Therefore, we compare the MHD and analytic model results with the observed magnetic field data from three flybys of Europa which include Alfvén wing crossings: E17, E25A, and E26.

Our results demonstrate that the perturbations during the E17 flyby do not show signals from local inhomogeneities in the atmosphere and can be explained by a plasma interaction with a radially symmetric atmosphere. The steep gradient in the magnetic field at the location of the Alfvén wing entry seen in the data provides information about the scale height of the atmosphere and the ionosphere. According to the analytic model results, an effective scale height of about 90 km fits the measured steep gradient in the data very well.

The measurements during the E25A flyby in the Alfvénic far field, in particular the B_y , component could be weakly influenced by an inhomogeneous atmosphere in the northern hemisphere especially by the ionospheric Hall effect according to the analytic model results. However, the modeling is inconclusive as discussed earlier. The MHD model results can not reproduce the B_y perturbations since the ionospheric Hall effect is not included in the MHD model.

Our analysis demonstrates that the magnetic field perturbations during the E26 flyby could be consistent with an atmospheric inhomogeneity on the southern hemisphere between the upstream and the Jupiter-facing side according to our results. The extent of the inhomogeneity in our model is similar to the plume derived by Roth *et al.* [2014a]. The inhomogeneity contains 50% of the gas content of the total atmosphere. The results also show that the magnetic field perturbation is very sensitive to the shape and the location of the inhomogeneity. However, we cannot exclude other effects which might cause comparable magnetic field perturbations, e.g., atmospheric day-night asymmetries, magnetospheric pressure balanced structures being convected over Europa, or flux tube interchange. With the previous searches [Roth *et al.*, 2014a, 2014b] the occurrence patterns of plumes could not be unveiled. The plumes could be sporadic events on unknown time scales and with uncertain locations. These temporal and spatial variabilities make the development of observational strategies difficult. The present study provides ideas how a future spacecraft mission to Europa could be able to detect and distinguish signals from plumes in the measured magnetic field and plasma data.

A more comprehensive data set recorded with sufficient time resolution is required such as the data set which will be taken by the planned Europa Mission. The results will therefore be helpful for the search of plumes at Europa during the JUICE mission of ESA and the Europa mission of NASA. Our findings suggest that signals from the plume can be detected in the magnetic field, the velocity field, and the density. Due to the locally increased neutral density in the atmosphere when a plume is present, collisional and mass loading processes increase at the location of the plume causing a local perturbation of the plasma parameters. The requirement for the detection of local plumes in the measured plasma density is that the spacecraft passes the center of the plume in the near field as close as possible. Plumes can also be detected on distant flybys in the Alfvénic far field. The local perturbation in the velocity and magnetic field due to the plume in Europa's near field maps out into the Alfvén wing along the Alfvén characteristics. To achieve a pronounced signal from the plume in the Alfvén wing it is important that the spacecraft trajectory crosses the center of the characteristics which are connected to the center of the plume, i.e., crosses the center of the Alfvén winglet that maps to the center of the plume. The farther away the spacecraft passes the center of the winglet, the more complicated is the

detection of plume signals in the data especially when an additional global asymmetry of the atmosphere is present as predicted by, e.g., *Pospieszalska and Johnson* [1989] or *Plainaki et al.* [2013]. Both velocity and magnetic field measurements are required to distinguish between a pure Alfvénic structure such as generated by a plume and magnetospheric structures that are convected across Europa and its Alfvén wings. Alfvénic structures generated at Europa will obey the relationship $\delta \underline{B} = \pm \sqrt{\mu_0 \rho_0} \delta \underline{v}$, while convecting magnetospheric signatures might simply be pressure-balanced structures. A perturbation in the density in the far field due to the plume will not or only barely be visible.

The implications are also interesting for other moons which show inhomogeneities in their atmospheres like, e.g., Io with its eruptive volcanoes.

Appendix A: MHD Model

A1. Scale Analysis of Terms in MHD Equations

We derived the single-fluid MHD equations from the two-fluid equations for one ion and one electron species where we included source terms describing electron impact ionization, dissociative recombination, and collisions between charged particles and neutrals. The two-fluid equations have been derived by taking velocity moments of the terms of Boltzmann's equation [e.g., *Schunk*, 1975; *Szegö et al.*, 2000]. The set of equations for the electrons and ions consists of the continuity, momentum, and energy equation as follows:

$$\partial_t n_s + \nabla \cdot (n_s \underline{v}_s) = \frac{\delta n_s}{\delta t} \quad (A1)$$

$$\rho_s (\partial_t \underline{v}_s + \underline{v}_s \cdot \nabla \underline{v}_s) + \nabla p_s - n_s q_s (\underline{E} + \underline{v}_s \times \underline{B}) = \frac{\delta \underline{M}_s}{\delta t} - m_s \underline{v}_s \frac{\delta n_s}{\delta t} \quad (A2)$$

$$\partial_t \epsilon_s + \nabla \cdot (\epsilon_s \underline{v}_s) + p_s \nabla \cdot \underline{v}_s = \frac{\delta E_s}{\delta t} \quad (A3)$$

with

$$\frac{\delta n_s}{\delta t} = P_s - L_s \quad (A4)$$

$$\frac{\delta \underline{M}_s}{\delta t} = -v_{s,n} \rho_s \underline{v}_s - L_s m_s \underline{v}_s \quad (A5)$$

$$\frac{\delta E_s}{\delta t} = \frac{m_s}{m_s + m_n} v_{s,n} n_s [3k_B(T_n - T_s) + m_n v_s^2] + \frac{1}{2} m_s v_s^2 P_s - \frac{3}{2} k_B T_s L_s. \quad (A6)$$

The index s stands for ions or electrons. The parameter n_s represents the number density, $\underline{v}_s$ is the bulk velocity, $\rho_s = m_s n_s$ is the mass density with the mass m_s , $p_s = n_s k_B T_s$ is the thermal pressure with the temperature T_s and the Boltzmann constant k_B , q_s is the charge, $\epsilon_s = \frac{3}{2} p_s$ is the internal energy density of the species s , $\underline{E}$ is the electric field, m_n and T_n are the mass and the temperature of the neutrals, $v_{s,n}$ is the momentum transfer collision frequency between species s and the neutrals, and P_s and L_s are the production and loss rates, respectively. In addition, $\frac{\delta n_s}{\delta t}$, $\frac{\delta \underline{M}_s}{\delta t}$, and $\frac{\delta E_s}{\delta t}$ are the net source, the change in momentum, and the local change in internal energy density, respectively, per unit volume of the fluid species s due to collisions, plasma production, and loss. Here it is assumed that the neutrals are at rest and that the distribution functions of the plasma species are isotropic in the plasma frame.

To derive the MHD equations, we consider one electron and one singly charged ion species. After combining equations (A1)–(A6) with Faraday's and Ampère's law, we find a set of complex one-fluid equations as follows:

$$\partial_t \rho + \nabla \cdot (\rho \underline{v}) = m_i (P - L) \quad (A7)$$

$$\rho (\partial_t \underline{v} + \underline{v} \cdot \nabla \underline{v}) = -\nabla p + \underline{j} \times \underline{B} - (\rho_e v_{en} + \rho_i \tilde{v}_{in}) \underline{v} - m_i P \underline{v} + \frac{m_e}{e} (v_{en} - \tilde{v}_{in}) \underline{j} - \frac{m_e}{e^2} \underline{j} \cdot \nabla \left(\frac{\underline{j}}{n} \right) \quad (A8)$$

$$\begin{aligned} \partial_t \underline{B} = \nabla \times \left(-\frac{m_e}{ne^2} \partial_t \underline{j} - \frac{m_e}{ne^2} \nabla \cdot (\underline{v} \underline{j} + \underline{j} \underline{v} - \frac{1}{en} \underline{j} \underline{j}) + \frac{1}{ne} \nabla \left(p_e - \frac{m_e}{m_i} p_i \right) + \underline{v} \times \underline{B} \right) \\ + \nabla \times \left(-\frac{1}{ne} (\underline{j} \times \underline{B}) + \frac{m_e}{e} (v_{en} - \tilde{v}_{in}) \underline{v} - \frac{m_e}{ne^2} \left(\frac{m_e}{m_i} \tilde{v}_{in} + v_{en} \right) \underline{j} - \frac{m_e}{n^2 e^2} \underline{j} \right) \end{aligned} \quad (A9)$$

$$\begin{aligned}
\partial_t \epsilon + \nabla \cdot (\epsilon \underline{v}) = & -p \nabla \cdot \underline{v} - \frac{3k_B}{2e} \nabla \cdot \left(\left(\frac{m_e}{m_i} T_i - T_e \right) \underline{j} \right) - \frac{1}{e} \left(\frac{m_e}{m_i} p_i - p_e \right) \nabla \cdot \left(\frac{\underline{j}}{n} \right) \\
& + \frac{\tilde{v}_{in} \rho}{m_i + m_n} \left(3k_B (T_n - T_i) + m_n \frac{m_e^2}{\rho^2 e^2} j^2 + 2 \frac{m_n m_e}{\rho e} \underline{j} \cdot \underline{v} + m_n v^2 \right) \\
& + \frac{n m_e v_{en}}{m_e + m_n} \left(3k_B (T_n - T_e) + \frac{m_n}{n^2 e^2} j^2 + m_n v^2 - \frac{2m_n}{ne} \underline{v} \cdot \underline{j} \right) \\
& + \frac{m_e}{n^2 e^2} P j^2 - \frac{3}{2} k_B L (T_e + T_i) + \frac{1}{2} m_i P v^2
\end{aligned} \tag{A10}$$

For the calculation, we applied several simplifications and assumptions: $m_e \ll m_i$, $n = n_e \approx n_i$, the total plasma mass density is $\rho = \rho_i + \rho_e \approx \rho_i$, the total plasma pressure is $p = p_i + p_e$, the current density is $\underline{j} = ne(\underline{v}_i - \underline{v}_e)$, the plasma bulk velocity is $\underline{v} = \frac{\rho_e \underline{v}_e + \rho_i \underline{v}_i}{\rho}$, and the total momentum transfer collision frequency between ions and neutrals $\tilde{v}_{in} = v_{in} + v_{ex}$ takes into account elastic collisions and charge exchange.

We performed a scale analysis to estimate the importance of each term for our problem. Therefore, we applied typical values of each plasma variable to evaluate the typical scale of each term in equations (A7)–(A10). Typical values used for our estimations can be found in Table A1. Typical scales for each term of the continuity (A7), momentum (A8), induction (A9), and energy density equation (A10) are presented in Tables A2–A5, respectively. In these tables the terms which are considered to be negligible are separated from the important terms by a horizontal line. In the next step, we removed the terms pertaining to small scales, because they do not alter the important physics of our model. Although, the loss terms in the continuity (A7) and energy density equations (A10) are of insignificant scales, we included them in our MHD equations, because they have been traditionally included in modeling of Europa's interaction [e.g., Saur et al., 1998; Schilling et al., 2007; Rubin et al., 2015]. Finally, we get the equations (1)–(4) of our MHD model.

Table A1. Typical Values for Each Plasma Variable

Plasma Variable	Typical Value
v_0 , Plasma bulk velocity	104 km s ^{−1}
R_E , Europa's radius	1569 km
B_0 , Background magnetic field	4.5×10^{-7} T
ρ_0 , Plasma mass density	4.93×10^8 amu m ^{−3}
$k_B T_e$, Electron temperature	100 eV ^a
$k_B T_i$, Ion temperature	100 eV ^a
$m_i = m_{O_2^+}$, Ion mass	32 amu
$m_n = m_{O_2}$, Mass of the neutrals	32 amu
$p_e = n_e k_B T_e$, Pressure of electrons	0.2 nPa
$p_i = n_i k_B T_i$, Pressure of ions	0.2 nPa
T_n , Temperature of the neutral gas	130 K
v_{in} , Ion-neutral collision frequency, equation (13) ^b	0.02 Hz
v_{en} , Electron-neutral collision frequency ^c	0.02 Hz
v_{ex} , Charge exchange frequency, equation (14) ^b	0.1 Hz
L , Recombination rate, equation (12) ^d	$6.0 \text{ m}^{-3} \text{ s}^{-1}$
P , Production rate, equation (8) ^{b,e}	$2.3 \times 10^7 \text{ m}^{-3} \text{ s}^{-1}$

^aKivelson et al. [2004].

^bIn the calculations a neutral number density $n_A(h = 100 \text{ km}) = 1.8 \times 10^{13} \text{ m}^{-3}$ was used.

^c $v_{en} = 10^{-15} n_A$ after Schilling et al. [2007].

^dFor the calculation of α_{rec} (equation (11)) the temperature of the ionospheric electrons (0.5 eV) was used.

^e $f_{imp}(T_e = 100 \text{ eV}) = 8.0 \times 10^{-14} \text{ m}^3 \text{ s}^{-1}$ was applied.

Table A2. Typical Scales for Each Term of the Continuity Equation^a

Term	Value
$\partial_t \rho^b$	1.0×10^0
$\nabla \cdot (\rho \underline{v})$	1.0×10^0
$m_i P$	2.2×10^1
$m_i L$	5.8×10^{-6}

^aThe terms below the horizontal line can be neglected because their typical scales are very small.

^bThe values were normed so that $\partial_t \rho$ is 1.

A2. Electron Impact Ionization

Electron impact ionization strongly depends on the temperature of the electrons T_e . Magnetospheric electrons which collide with the neutral particles in the atmosphere are locally cooled down. The electrons, which loose energy due to the electron impact process with the atmospheric neutrals, can be reheated by the energy reservoir provided by the plasma torus. Energy is transported via heat conduction along the magnetic field lines from the plasma torus to the cooler regions of the flux tubes. *Saur et al.* [1998] show that this process is very effective at Europa which results in weak temperature gradients along the field lines. In our MHD model, T_e is not calculated self-consistently. To approximately account for the effect of heat conduction and to ensure conservation of energy, we apply the following description: First, we consider the electron energy flux F_{Torus} from the plasma torus, which is available for the reheating of the cooled magnetospheric electrons:

$$F_{\text{Torus}} = \frac{3}{2} n_0 k_B T_e v_0 D_{\text{tube}} L_{\text{Torus}} \quad (\text{A11})$$

$$= \frac{3}{2} n_0 k_B T_e v_0 2(R_E + H_0) \alpha_{\text{plasma}} L_{\text{Torus}} \quad (\text{A12})$$

This flux is based on the total flux tube energy, which is convected across Europa. We additionally assume that electron heat conduction parallel to the magnetic field very effectively transports electron energy within the flux tube above and below Europa into the ionosphere. The electron temperature in our model is assumed to be constant along the magnetic field lines. $L_{\text{Torus}} = 1.7 R_J$ is the vertical extent of the plasma torus with Jupiter's radius R_J [Bagenal and Delamere, 2011]. D_{tube} is the width of the flux tubes approaching the interaction region. The upstream width of the flux tube $2(R_E + H_0)$ changes when it is convected across Europa depending on the strength of the plasma interaction. It decreases by the factor α_{plasma} , which is given by

$$\alpha_{\text{plasma}} = v_{\text{wing}} / v_0 \quad (\text{A13})$$

Table A3. Typical Scales for Each Term of the Velocity Equation^a

Term	Value
$\rho \partial_t \underline{v}^b$	1.0×10^0
$\rho \underline{v} \cdot \nabla \underline{v}$	1.0×10^0
∇p	5.6×10^{-2}
$\underline{j} \times \underline{B}$	1.8×10^{-3}
$m_i P \underline{v}$	2.2×10^1
$\rho_i \tilde{v}_{\text{in}} \underline{v}$	2.1×10^0
$\rho_e v_{\text{en}} \underline{v}$	4.8×10^{-6}
$\frac{m_e}{e} \tilde{v}_{\text{in}} \underline{j}$	3.1×10^{-9}
$\frac{m_e}{e} v_{\text{en}} \underline{j}$	4.2×10^{-10}
$\frac{m_e}{e^2} \underline{j} \cdot \nabla \left(\frac{\underline{j}}{n} \right)$	1.4×10^{-13}

^aThe terms below the horizontal line can be neglected because their typical scales are very small.

^bThe values were normed so that $\rho \partial_t \underline{v}$ is 1.

Table A4. Typical Scales for Each Term of the Induction Equation^a

Term	Value
$\partial_t \underline{B}$ ^b	1.0×10^0
$\nabla \times (\underline{v} \times \underline{B})$	1.0×10^0
$\nabla \times \left(\frac{1}{ne} \nabla p_e \right)$	1.4×10^{-3}
$\nabla \times \left(\frac{1}{ne} \underline{j} \times \underline{B} \right)$	8.9×10^{-5}
$\nabla \times \left(\frac{m_e}{e} \tilde{v}_{in} \underline{v} \right)$	1.7×10^{-6}
$\nabla \times \left(\frac{m_e}{e} v_{en} \underline{v} \right)$	2.3×10^{-7}
$\nabla \times \left(\frac{1}{ne} \nabla \frac{m_e}{m_i} \rho_i \right)$	2.3×10^{-8}
$\nabla \times \frac{m_e}{ne^2} \partial_t \underline{j}$	7.5×10^{-11}
$\nabla \times \frac{m_e}{ne^2} \nabla \cdot (\underline{v} \underline{j})$	7.5×10^{-11}
$\nabla \times \frac{m_e}{ne^2} \nabla \cdot (\underline{j} \underline{v})$	7.5×10^{-11}
$\nabla \times \left(\frac{m_e}{ne^2} v_{en} \underline{j} \right)$	2.1×10^{-11}
$\nabla \times \frac{m_e}{ne^2} \nabla \cdot \left(\frac{1}{en} \underline{j} \underline{j} \right)$	6.6×10^{-15}
$\nabla \times \left(\frac{m_e}{ne^2} \left(\frac{m_e}{m_i} \tilde{v}_{in} \right) \underline{j} \right)$	2.6×10^{-15}
$\nabla \times \left(\frac{m_e}{n^2 e^2} \underline{j} \right)$	4.4×10^{-16}

^aThe terms below the horizontal line can be neglected because their typical scales are very small.

^bThe values were normed so that $\partial_t \underline{B}$ is 1.

It is the ratio between the x component of the perturbed plasma velocity inside the Alfvén wing v_{wing} and the unperturbed upstream plasma velocity v_0 . This factor is a measure of the fraction of the upstream plasma flow that can enter Europa's ionosphere and can also be expressed by conductances [e.g., *Southwood and Dunlop, 1984*]:

$$\alpha_{\text{plasma}} = \frac{2\Sigma_A}{\Sigma_p + 2\Sigma_A}. \quad (\text{A14})$$

We determine the perturbed plasma velocity inside the Alfvén wing at a distance of $3 R_E$ following the northern characteristic. The maximum energy flux which is lost due to electron impact ionization within Europa's atmosphere is calculated by

$$F_{\text{lost}} = f_{\text{imp,max}} n_0 E_{\text{ion,eff}} \int_{R_E}^{\infty} \int_0^{2\pi} \int_0^{\pi} n_n(r, \phi, \theta) dV. \quad (\text{A15})$$

For the effective ionization energy of O_2 we use $E_{\text{ion,eff}} = 32 \text{ eV}$ [*Banks and Kockarts, 1973*].

The ionization rate by the background magnetospheric plasma $f_{\text{imp},0}$ represents in our calculation an upper limit for the applicable ionization rate. The $f_{\text{imp},0}$ for a specific electron temperature is calculated by [*Banks and Kockarts, 1973*]

$$f_{\text{imp},0}(T_e) = \int_{E_{\text{ion}}}^{\infty} dE f_E(E) \sigma_{\text{imp}}(E) v_{\text{el}}(E) \quad (\text{A16})$$

with the normalized Maxwellian distribution function in energy space

$$f_E(E) = \frac{2\sqrt{E}}{\pi} (k_B T_e)^{-\frac{3}{2}} \exp\left(-\frac{E}{k_B T_e}\right), \quad (\text{A17})$$

the kinetic electron velocity at a given energy

$$v_{\text{el}}(E) = \sqrt{\frac{2E}{m_e}}, \quad (\text{A18})$$

Table A5. Typical Scales for Each Term of the Energy Equation^a

Term	Value
$\partial_t \epsilon^b$	1.0×10^0
$\nabla \cdot (\epsilon \nabla)$	1.0×10^0
$p \nabla \cdot \underline{v}$	6.7×10^{-1}
$\frac{1}{2} m_i p v^2$	1.3×10^2
$\frac{\tilde{v}_{in} \rho}{m_i + m_n} m_n v^2$	1.2×10^1
$\frac{\tilde{v}_{in} \rho}{m_i + m_n} 3k_B T_i$	1.0×10^0
$\frac{\tilde{v}_{in} \rho}{m_i + m_n} 3k_B T_n$	1.2×10^{-4}
$\frac{nm_e v_{en}}{m_e + m_n} m_n v^2$	5.7×10^{-5}
$\frac{3k_B}{2e} \nabla \cdot \left(T_e \underline{j} \right)$	4.4×10^{-5}
$\frac{1}{e} p_e \nabla \cdot \left(\frac{\underline{j}}{n} \right)$	3.0×10^{-5}
$\frac{nm_e v_{en}}{m_e + m_n} 3k_B T_e$	4.8×10^{-6}
$\frac{3}{2} k_B L T_i$	3.0×10^{-6}
$\frac{3}{2} k_B L T_e$	3.0×10^{-6}
$\frac{\tilde{v}_{in} \rho}{m_i + m_n} 2 \frac{m_n m_e}{\rho e} \underline{j} \cdot \underline{v}$	7.5×10^{-8}
$\frac{nm_e v_{en}}{m_e + m_n} \frac{2m_n}{ne} \underline{v} \cdot \underline{j}$	1.0×10^{-8}
$\frac{3k_B}{2e} \nabla \cdot \left(\frac{m_e}{m_i} T_i \underline{j} \right)$	7.6×10^{-10}
$\frac{nm_e v_{en}}{m_e + m_n} 3k_B T_n$	5.3×10^{-10}
$\frac{1}{e} \frac{m_e}{m_i} p_i \nabla \cdot \left(\frac{\underline{j}}{n} \right)$	5.1×10^{-10}
$\frac{m_e}{n^2 e^2} p j^2$	3.4×10^{-12}
$\frac{nm_e v_{en}}{m_e + m_n} \frac{m_n}{n^2 e^2} j^2$	4.5×10^{-13}
$\frac{\tilde{v}_{in} \rho}{m_i + m_n} m_n \frac{m_e^2}{\rho^2 e^2} j^2$	2.9×10^{-17}

^aThe terms below the horizontal line can be neglected because their typical scales are very small.

^bThe values were normed so that $\partial_t \epsilon$ is 1.

and the ionization cross sections $\sigma_{\text{imp}}(E)$ for O_2 adopted from *Hwang et al.* [1996]. E_{ion} is the threshold for ionization of O_2 . In order to obey energy conservation we take into account that the energy flux that is available from the plasma torus for the reheating of the cooled magnetospheric electrons needs to be larger than the energy flux which is used up by electron impact ionization ($F_{\text{lost}} \leq F_{\text{Torus}}$). To ensure that this condition is fulfilled at every time step in our MHD simulations, we compute the maximum possible ionization rate $f_{\text{imp,max}}$. This is done by equating $F_{\text{Torus}} = F_{\text{lost}}$:

$$f_{\text{imp,max}} = \frac{3k_B T_e v_0 (R_E + H) \alpha_{\text{Plasma}} L_{\text{Torus}}}{E_{\text{ion,eff}} \int n_n dV}. \quad (\text{A19})$$

The electron impact ionization rate in equation (8) is then calculated in the following way:

$$f_{\text{O}_2} = \begin{cases} f_{\text{imp,max}} & \text{for } f_{\text{imp,max}} \leq f_{\text{imp,0}} \\ f_{\text{imp,0}} & \text{for } f_{\text{imp,max}} > f_{\text{imp,0}} \end{cases} \quad (\text{A20})$$

where f_{O_2} is controlled by the strength of the plasma interaction to avoid overestimation of the plasma production.

Appendix B: Analytic Model of the Plasma Interaction

Europa's conductive ionosphere acts as an obstacle to the unperturbed plasma flow. The electrodynamic interaction creates a current system composed of ionospheric currents, Alfvén wing currents, and additional

hemisphere coupling currents when an asymmetric atmosphere is present. In this section we present an analytic solution of the electric potential for asymmetric ionospheric quantities and for a constant magnetic field. Note that this solution is only applicable for the Alfvénic far field. Sketches of the constant ionospheric conductances and the geometry of the electric current system are displayed in Figures 1 and 2. We aim to elucidate with this solution the implications of an atmospheric inhomogeneity in a global atmosphere on Europa's plasma interaction in the Alfvénic far field. Although the electric potential is reduced to two dimensions, the ionospheric conductivities and the ionospheric current system is three dimensional. In analogy to the calculations of *Saur et al.* [2007] we apply the following approach in polar coordinates ($x = r \cos \phi$ and $y = r \sin \phi$):

$$\hat{\Phi}(\hat{r}, \phi) = \sum_{l=1}^{\infty} [\hat{r}^l (a_l \sin(l\phi) + b_l \cos(l\phi)) + \hat{r}^{-l} (g_l \sin(l\phi) + h_l \cos(l\phi))] \quad (B1)$$

for the solution of the Laplace equation $\Delta\Phi(x, y) = 0$, where we use $\hat{r} = r/R$ for the radial component and $\hat{\Phi} = \Phi/\Phi_0$ for the electric potential with the radius of the moon R , the unperturbed electric potential $\Phi_0 = E_0 R$, and the unperturbed corotational electric field E_0 . The constants a_l, b_l, g_l , and h_l are to be determined from the boundary conditions. Note, within each area of constant conductances where the Laplace equation needs to be solved, a separate set of a_l, b_l, g_l , and h_l have to be calculated. The solution for the electric potential should fulfill the boundary and the jump conditions. Additionally, it has to be continuous without singularities. Only coefficients with $l = 1$ are nonzero because the perturbed electric field vanishes at infinity and the potential is given by

$$\Phi_0 = E_0 y \quad \text{for } r \rightarrow \infty. \quad (B2)$$

We subdivide our interaction region in five domains (see Figure 2): In the external domain, where the field lines do not intersect the solid body and the ionospheric conductances vanish, the electric potential with superscript e is given by

$$\hat{\Phi}^e(\hat{r}, \phi) = \hat{r} \sin(\phi) + \hat{r}^{-1} (g_1^e \sin(\phi) + h_1^e \cos(\phi)) \quad \text{for } \hat{r}_{a,8} \leq \hat{r}. \quad (B3)$$

The domain with superscript a represents the area where the conductances peak and decrease approximately in an exponential form, when moving outward and where the currents feed into the global ionosphere are located. The potential in this area is given by

$$\hat{\Phi}^{a,k}(\hat{r}, \phi) = \hat{r} (a_1^{a,k} \sin(\phi) + b_1^{a,k} \cos(\phi)) + \hat{r}^{-1} (g_1^{a,k} \sin(\phi) + h_1^{a,k} \cos(\phi)) \quad \text{for } \hat{r}_{a,k-1} < \hat{r} \leq \hat{r}_{a,k}. \quad (B4)$$

This exponential-ionospheric domain is subdivided into eight regions in order to construct the decrease of the conductances as visible in Figure 1. The index k runs from 1 to 8 and $r_{a,0} = r_s$ correspond to the radius of the moon. In each region the conductances $\Sigma_{p,H}^{a,k}$ are constant and each region is spatially limited by $r_{a,k}$. The conductances are constructed in the way that

$$\Sigma_{p,H}^{a,k} = \Sigma_{p,H}^{a,1} \exp(-(k-1)\Delta/\tilde{H}). \quad (B5)$$

For the step size Δ we chose a value of $0.04 r_s$. Here we introduced the effective scale height $\tilde{H}$. Our purpose with the approximation to an exponentially decreasing ionospheric domain is to investigate if the steep gradient seen in the measured magnetic field when Galileo crossed the Alfvén wing during the E17 flyby can be explained by Europa's global atmosphere. Therefore, we consider the average electron density which has its maximum near the surface. The average profile of the electron density is best described by an exponential decrease with altitude with a model having a plasma scale height of $H_e = 240 \pm 40$ km below 300 km according to the results of *Kliore et al.* [1997]. We describe Europa's global atmosphere radially symmetric (equation (6)). The atmospheric neutral density is described by an exponential decrease in altitude. The Pedersen conductivity depends approximately on the product of the electron and the neutral density which is particularly correct farther away from the surface. Thus, we assume for the linear Pedersen conductivity $\sigma_p \sim \exp\left(\frac{h}{H_e} + \frac{h}{H_a}\right)$. The effective scale height is then given by

$$\tilde{H} = \frac{H_a H_e}{H_a + H_e}. \quad (B6)$$

For the atmospheric scale height we choose $H_a = 145$ km [*Saur et al.*, 1998; *Roth et al.*, 2016] and for the plasma scale height $H_e = 240$ km [*Kliore et al.*, 1997] (see discussion in section 3.4.1). The spatial extent of domain a

strongly depends on the effective scale height. In the northern hemisphere we assume a global atmosphere with constant conductances $\Sigma_{p,H}^n$. Thus, the electric potential within the northern tube is given by

$$\hat{\Phi}^n(\hat{r}, \phi) = \hat{r} (a_1^n \sin(\phi) + b_1^n \cos(\phi)) \quad \text{for } \hat{r} \leq \hat{r}_s. \quad (B7)$$

In this calculation the inhomogeneity with conductances $\Sigma_{p,H}^p$ is assumed to lie at the south pole of the moon and the electric potential in domain p is calculated by

$$\hat{\Phi}^p(\hat{r}, \phi) = \hat{r} (a_1^p \sin(\phi) + b_1^p \cos(\phi)) \quad \text{for } \hat{r} \leq \hat{r}_p. \quad (B8)$$

The region outside of the dense inhomogeneity is characterized by the electric potential with superscript s :

$$\hat{\Phi}^s(\hat{r}, \phi) = \hat{r} (a_1^s \sin(\phi) + b_1^s \cos(\phi)) + \hat{r}^{-1} (g_1^s \sin(\phi) + h_1^s \cos(\phi)) \quad \text{for } \hat{r}_p \leq \hat{r} \leq \hat{r}_s. \quad (B9)$$

The free parameters a_1^j , b_1^j , g_1^j and h_1^j with the superscript $j = e, a, n, s$, and p depend on the conductances within each domain and the spatial limitations of each domain. To compute these constants, we have to consider the boundary conditions between individual domains. The electric potential has to be continuous at the boundaries of the domains, so $\hat{\Phi}^e(\hat{r} = \hat{r}_{a,8}) = \hat{\Phi}^{a,8}(\hat{r} = \hat{r}_{a,8})$, $\hat{\Phi}^{a,8}(\hat{r} = \hat{r}_{a,7}) = \hat{\Phi}^{a,7}(\hat{r} = \hat{r}_{a,7})$, ..., $\hat{\Phi}^{a,2}(\hat{r} = \hat{r}_{a,1}) = \hat{\Phi}^{a,1}(\hat{r} = \hat{r}_{a,1})$, $\hat{\Phi}^{a,1}(\hat{r} = \hat{r}_s) = \hat{\Phi}^n(\hat{r} = \hat{r}_s) = \hat{\Phi}^s(\hat{r} = \hat{r}_s)$, and $\hat{\Phi}^s(\hat{r} = \hat{r}_p) = \hat{\Phi}^p(\hat{r} = \hat{r}_p)$. The condition of continuity does not hold for the normal component of the electric potential. For the boundaries at the domain at r_p and r_a we use the jump condition [Saur et al., 1999, equation (A2)]

$$\lim_{\epsilon \rightarrow 0} \left[r (\Sigma_p + \Sigma_A) \frac{\partial \Phi}{\partial r} + \Sigma_H \frac{\partial \Phi}{\partial \phi} \right]_{r_j - \epsilon}^{r_j + \epsilon} = 0 \quad (B10)$$

with $r_j = r_{p,a}$. At $r = r_s$ the hemisphere coupling occurs and the potentials $\Phi^{a,1}$, Φ^s , and Φ^n are linked through equation (9) in the work of Saur et al. [2007]. We apply a computer algebra program to calculate the 42 free parameters from the boundary and jump conditions. The equations for the electric potential (B3)–(B9) are uniquely solved. The calculation of the electric potential for a north polar inhomogeneity is analogous.

In the Alfvén wings the frozen-in-field theorem holds, so the electric field is given by $\underline{E} = -\underline{v} \times \underline{B}$. The analytic model is based on pure Alfvénic interaction in the far field so the perturbed magnetic field $\delta \underline{B}$ and velocity $\delta \underline{v}$ are related by $\delta \underline{B} = \pm \sqrt{\mu_0 \rho_0} \delta \underline{v}$. Combining these relationships it is possible to calculate the perturbed magnetic field from the electric field [Neubauer, 1980]. Neubauer [1980] uses a coordinate system with the z axis aligned with either the northern or the southern Alfvén characteristic. The northern ($\underline{c}_A^+$) and southern ($\underline{c}_A^-$) Alfvén characteristics are given by

$$\underline{c}_A^\pm = \underline{v}_0 \pm \underline{B}_0 / (\sqrt{\mu_0 \rho_0}). \quad (B11)$$

The y axis in the system of Neubauer [1980] is the same as in the EPhiB system and the x axis completes the right-handed coordinate system. Transforming equations (14) and (15) of his work into the EPhiB system leads to the expression of the magnetic field for the Alfvénic far field:

$$\underline{B} = \frac{1}{\sqrt{1 + M_A^2}} \begin{pmatrix} \mp \mu_0 \Sigma_A E_y \mp M_A \sqrt{B_0^2 - \mu_0^2 \Sigma_A^2 \left(E_y^2 + \frac{1}{1 + M_A^2} E_x^2 \right)} \\ \pm \mu_0 \Sigma_A E_x \\ \mu_0 \Sigma_A M_A E_y - \sqrt{B_0^2 - \mu_0^2 \Sigma_A^2 \left(E_y^2 + \frac{1}{1 + M_A^2} E_x^2 \right)} \end{pmatrix}, \quad (B12)$$

where $\underline{B}$ and $\underline{E}$ are given in the EPhiB system. The upper and lower signs refer to the northern and southern Alfvén wings, respectively. The Alfvén conductance is given by

$$\Sigma_A = \frac{1}{\mu_0 v_{A_0} \sqrt{1 + M_A^2}} \quad (B13)$$

for low Alfvénic Mach numbers M_A [Neubauer, 1980]. The parameter v_{A_0} is the Alfvén velocity of the upstream plasma. Incorporating our solutions for the electric potential given in equations (B3)–(B9) in the calculations of the magnetic field allows us to calculate the magnetic field in the Alfvénic far field for our specific problem. It is not applicable to calculate the magnetic field perturbation in the near field since local ionospheric effects become important in this region.

The calculations made here are based on the fact that the chosen geometry of the conductances possesses rotational symmetry around the z axis. A breakup of this symmetry, for example, by choosing a position for the inhomogeneity away from the north or south pole, would make the calculations exceedingly complex. The real plasma interaction is not purely Alfvénic and the interaction region is much more complex. However, the here presented approach is useful for a first analysis to search for potential local atmospheric inhomogeneities in the magnetic field and, if available, plasma velocity data.

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References

- Bagenal, F., and P. A. Delamere (2011), Flow of mass and energy in the magnetospheres of Jupiter and Saturn, *J. Geophys. Res.*, **116**, A05209, doi:10.1029/2010JA016294.
- Bagenal, F., E. Sidrow, R. J. Wilson, T. A. Cassidy, V. Dols, F. J. Cray, A. J. Steffl, P. A. Delamere, W. S. Kurth, and W. R. Paterson (2015), Plasma conditions at Europa's orbit, *Icarus*, **261**, 1–13, doi:10.1016/j.icarus.2015.07.036.
- Banks, P. (1966), Collision frequencies and energy transfer. Ions, *Planet. Space Sci.*, **14**, 1105–1122, doi:10.1016/0032-0633(66)90025-0.
- Banks, P. M., and G. Kockarts (1973), *Aeronomy, Part A*, Academic Press, New York and London.
- Baumjohann, W., and R. A. Treumann (1996), *Basic Space Plasma Physics*, Imperial College Press, London.
- Cassidy, T. A., R. E. Johnson, M. A. McGrath, M. C. Wong, and J. F. Cooper (2007), The spatial morphology of Europa's near-surface O_2 atmosphere, *Icarus*, **191**, 755–764, doi:10.1016/j.icarus.2007.04.033.
- Chané, E., J. Saur, S. Poedts, and J. Geophys. Res. Space Physics (2013), Modeling Jupiter's magnetosphere: Influence of the internal sources, **118**, 2157–2172, doi:10.1002/jgra.50258.
- Dols, V. J., F. Bagenal, T. A. Cassidy, F. J. Cray, and P. A. Delamere (2016), Europa's atmospheric neutral escape: Importance of symmetrical O_2 charge exchange, *Icarus*, **264**, 387–397, doi:10.1016/j.icarus.2015.09.026.
- Duling, S., J. Saur, and J. Wicht (2014), Consistent boundary conditions at nonconducting surfaces of planetary bodies: Applications in a new Ganymede MHD model, *J. Geophys. Res. Space Physics*, **119**, 4412–4440, doi:10.1002/2013JA019554.
- Eviatar, A., and C. Paranicas (2005), The plasma plumes of Europa and Callisto, *Icarus*, **178**, 360–366, doi:10.1016/j.icarus.2005.06.007.
- Goertz, C. K. (1980), Io's interaction with the plasma torus, *J. Geophys. Res.*, **85**, 2949–2956, doi:10.1029/JA085iA06p02949.
- Hall, D. T., D. F. Strobel, P. D. Feldman, M. A. McGrath, and H. A. Weaver (1995), Detection of an oxygen atmosphere on Jupiter's moon Europa, *Nature*, **373**, 677–679, doi:10.1038/373677a0.
- Hall, D. T., P. D. Feldman, M. A. McGrath, and D. F. Strobel (1998), The far-ultraviolet oxygen airglow of Europa and Ganymede, *Astrophys. J.*, **499**, 475–481.
- Hayes, J. C., M. L. Norman, R. A. Fiedler, J. O. Bordner, P. S. Li, S. E. Clark, A. ud-Doula, and M.-M. Mac Low (2006), Simulating radiating and magnetized flows in multiple dimensions with ZEUS-MP, *Astrophys. J. Suppl. Ser.*, **165**, 188–228, doi:10.1086/504594.
- Hwang, W., Y.-K. Kim, and M. E. Rudd (1996), New model for electron-impact ionization cross sections of molecules, *J. Chem. Phys.*, **104**, 2956–2966, doi:10.1063/1.471116.
- Intriligator, D. S., and W. D. Miller (1982), First evidence for a Europa plasma torus, *J. Geophys. Res.*, **87**, 8081–8090, doi:10.1029/JA087iA10p08081.
- Johnson, R. E. (2004), The magnetospheric plasma-driven evolution of satellite atmospheres, *Astrophys. J. Lett.*, **609**, L99–L102, doi:10.1086/422912.
- Johnson, R. E., M. H. Burger, T. A. Cassidy, F. Leblanc, M. Marconi, and W. H. Smyth (2009), Composition and detection of Europa's sputter-induced atmosphere, in *Europa, The University of Arizona Space Sci. Ser.*, edited by R. T. Pappalardo et al., pp. 507–527, Univ. of Arizona Press, Tucson.
- Kabin, K., M. R. Combi, T. I. Gombosi, A. F. Nagy, D. L. DeZeeuw, and K. G. Powell (1999), On Europa's magnetospheric interaction: A MHD simulation of the E4 flyby, *J. Geophys. Res.*, **104**, 19,983–19,992, doi:10.1029/1999JA000263.
- Khurana, K. K., M. G. Kivelson, D. J. Stevenson, G. Schubert, C. T. Russell, R. J. Walker, and C. Polanskey (1998), Induced magnetic fields as evidence for subsurface oceans in Europa and Callisto, *Nature*, **395**, 777–780, doi:10.1038/27394.
- Kivelson, M. G., K. K. Khurana, S. Joy, C. T. Russell, D. J. Southwood, R. J. Walker, and C. Polanskey (1997), Europa's magnetic signature: Report from Galileo's pass on 19 December 1996, *Science*, **276**, 1239–1241, doi:10.1126/science.276.5316.1239.
- Kivelson, M. G., K. K. Khurana, D. J. Stevenson, L. Bennett, S. Joy, C. T. Russell, R. J. Walker, C. Zimmer, and C. Polanskey (1999), Europa and Callisto: Induced or intrinsic fields in a periodically varying plasma environment, *J. Geophys. Res.*, **104**, 4609–4626, doi:10.1029/1998JA000095.
- Kivelson, M. G., F. Bagenal, W. S. Kurth, F. M. Neubauer, C. Paranicas, and J. Saur (2004), Magnetospheric interactions with satellites, in *Jupiter. The Planet, Satellites and Magnetosphere, Cambridge Planet. Sci.*, vol. 1, edited by F. Bagenal et al., pp. 513–536, Cambridge Univ. Press, Cambridge, U. K.
- Kivelson, M. G., K. K. Khurana, and M. Volwerk (2009), Europa's interaction with the Jovian magnetosphere, in *Europa, The Univ. of Arizona Space Sci. Ser.*, edited by R. T. Pappalardo et al., pp. 545, Univ. of Arizona Press, Tucson.
- Kliore, A. J., D. P. Hinson, F. M. Flasar, A. F. Nagy, and T. E. Cravens (1997), The ionosphere of Europa from Galileo radio occultations, *Science*, **277**, 355–358.
- Lagg, A., N. Krupp, J. Woch, and D. J. Williams (2003), In-situ observations of a neutral gas torus at Europa, *Geophys. Res. Lett.*, **30**(11), 1556, doi:10.1029/2003GL017214.
- Lipatov, A. S., J. F. Cooper, W. R. Paterson, E. C. Sittler, R. E. Hartle, and D. G. Simpson (2010), Jovian plasma torus interaction with Europa: 3D hybrid kinetic simulation. First results, *Planet. Space Sci.*, **58**, 1681–1691, doi:10.1016/j.pss.2010.06.015.
- Lipatov, A. S., J. F. Cooper, W. R. Paterson, E. C. Sittler, R. E. Hartle, and D. G. Simpson (2013), Jovian plasma torus interaction with Europa. Plasma wake structure and effect of inductive magnetic field: 3D hybrid kinetic simulation, *Planet. Space Sci.*, **77**, 12–24, doi:10.1016/j.pss.2013.01.009.
- Liu, Y., A. F. Nagy, K. Kabin, M. R. Combi, D. L. DeZeeuw, T. I. Gombosi, and K. G. Powell (2000), Two-species, 3D, MHD simulation of Europa's interaction with Jupiter's magnetosphere, *Geophys. Res. Lett.*, **27**, 1791–1794, doi:10.1029/1999GL003734.
- Mauk, B. H., D. G. Mitchell, S. M. Krimigis, E. C. Roelof, and C. P. Paranicas (2003), Energetic neutral atoms from a trans-Europa gas torus at Jupiter, *Nature*, **421**, 920–922.
- Neubauer, F. M. (1980), Nonlinear standing Alfvén wave current system at Io: Theory, *J. Geophys. Res.*, **85**, 1171–1178.
- Neubauer, F. M. (1998), The sub-Alfvénic interaction of the Galilean satellites with the Jovian magnetosphere, *J. Geophys. Res.*, **103**, 19,843–19,866.

- Neubauer, F. M. (1999), Alfvén wings and electromagnetic induction in the interiors: Europa and Callisto, *J. Geophys. Res.*, *104*, 28,671–28,684, doi:10.1029/1999JA900217.
- Norman, M. L. (2000), Introducing ZEUS-MP: A 3D, parallel, multiphysics code for astrophysical fluid dynamics, *Rev. Mex. Astron. Astrofis. Conf. Ser.*, *9*, 66–71.
- Paranicas, C., R. W. Carlson, and R. E. Johnson (2001), Electron bombardment of Europa, *Geophys. Res. Lett.*, *28*, 673–676, doi:10.1029/2000GL012320.
- Paranicas, C., J. M. Ratliff, B. H. Mauk, C. Cohen, and R. E. Johnson (2002), The ion environment near Europa and its role in surface energetics, *Geophys. Res. Lett.*, *29*(5), 1074, doi:10.1029/2001GL014127.
- Paranicas, C., J. F. Cooper, H. B. Garrett, R. E. Johnson, and S. J. Sturmer (2009), Europa's radiation environment and its effects on the surface, in *Europa, The University of Arizona Space Sci. Ser.*, edited by R. T. Pappalardo et al., pp. 529–544, Univ. of Arizona Press, Tucson.
- Paterson, W. R., L. A. Frank, and K. L. Ackerson (1999), Galileo plasma observations at Europa: Ion energy spectra and moments, *J. Geophys. Res.*, *104*, 22,779–22,792, doi:10.1029/1999JA900191.
- Plainaki, C., A. Milillo, A. Mura, S. Orsini, S. Massetti, and T. Cassidy (2012), The role of sputtering and radiolysis in the generation of Europa exosphere, *Icarus*, *218*, 956–966, doi:10.1016/j.icarus.2012.01.023.
- Plainaki, C., A. Milillo, A. Mura, J. Saur, S. Orsini, and S. Massetti (2013), Exospheric O₂ densities at Europa during different orbital phases, *Planet. Space Sci.*, *88*, 42–52, doi:10.1016/j.pss.2013.08.011.
- Pospieszalska, M. K., and R. E. Johnson (1989), Magnetospheric ion bombardment profiles of satellites—Europa and Dione, *Icarus*, *78*, 1–13.
- Roth, L., J. Saur, K. D. Retherford, D. F. Strobel, and J. R. Spencer (2011), Simulation of Io's auroral emission: Constraints on the atmosphere in eclipse, *Icarus*, *214*, 495–509.
- Roth, L., J. Saur, K. D. Retherford, D. F. Strobel, P. D. Feldman, M. A. McGrath, and F. Nimmo (2014a), Transient water vapor at Europa's South Pole, *Science*, *343*, 171–174, doi:10.1126/science.1247051.
- Roth, L., K. D. Retherford, J. Saur, D. F. Strobel, P. D. Feldman, M. A. McGrath, and F. Nimmo (2014b), Orbital apocenter is not a sufficient condition for HST/STIS detection of Europa's water vapor aurora, *Proc. Natl. Acad. Sci. U.S.A.*, *111*(48), E5123–E5132, doi:10.1073/pnas.1416671111.
- Roth, L., J. Saur, K. D. Retherford, D. F. Strobel, P. D. Feldman, M. A. McGrath, J. R. Spencer, A. Blöcker, and N. Ivchenko (2016), Europa's far ultraviolet oxygen aurora from a comprehensive set of HST observations, *J. Geophys. Res. Space Physics*, *121*, 2143–2170, doi:10.1002/2015JA022073.
- Rubin, M., et al. (2015), Self-consistent multifluid MHD simulations of Europa's exospheric interaction with Jupiter's magnetosphere, *J. Geophys. Res. Space Physics*, *120*, 3503–3524, doi:10.1002/2015JA021149.
- Russell, C. T., D. E. Huddleston, K. K. Khurana, and M. G. Kivelson (1998), The fluctuating magnetic field in the middle Jovian magnetosphere: Initial Galileo observations, *Planet. Space Sci.*, *47*, 133–142.
- Saur, J., D. F. Strobel, and F. M. Neubauer (1998), Interaction of the Jovian magnetosphere with Europa: Constraints on the neutral atmosphere, *J. Geophys. Res.*, *103*, 19,947–19,962, doi:10.1029/97JE03556.
- Saur, J., F. M. Neubauer, D. F. Strobel, and M. E. Summers (1999), Three-dimensional plasma simulation of Io's interaction with the Io plasma torus: Asymmetric plasma flow, *J. Geophys. Res.*, *104*, 25,105–25,126, doi:10.1029/1999JA900304.
- Saur, J., D. F. Strobel, F. M. Neubauer, and M. E. Summers (2003), The ion mass loading rate at Io, *Icarus*, *163*, 456–468.
- Saur, J., F. M. Neubauer, and N. Schilling (2007), Hemisphere coupling in Enceladus' asymmetric plasma interaction, *J. Geophys. Res.*, *112*, A11209, doi:10.1029/2007JA012479.
- Saur, J., F. M. Neubauer, and K.-H. Glassmeier (2010), Induced magnetic fields in solar system bodies, *Space Sci. Rev.*, *152*, 391–421.
- Saur, J., P. D. Feldman, L. Roth, F. Nimmo, D. F. Strobel, K. D. Retherford, M. A. McGrath, N. Schilling, J.-C. Gérard, and D. Grodent (2011), Hubble space telescope/advanced camera for surveys observations of Europa's atmospheric ultraviolet emission at Eastern Elongation, *Astrophys. J.*, *738*, 153, doi:10.1088/0004-637X/738/2/153.
- Saur, J., T. Grambusch, S. Duling, F. M. Neubauer, and S. Simon (2013), Magnetic energy fluxes in sub-Alfvénic planet star and moon planet interactions, *Astron. Astrophys.*, *552*, A119.
- Schilling, N., K. K. Khurana, and M. G. Kivelson (2004), Limits on an intrinsic dipole moment in Europa, *J. Geophys. Res.*, *109*, E05006, doi:10.1029/2003JE002166.
- Schilling, N., F. M. Neubauer, and J. Saur (2007), Time-varying interaction of Europa with the Jovian magnetosphere: Constraints on the conductivity of Europa's subsurface ocean, *Icarus*, *192*, 41–55, doi:10.1016/j.icarus.2007.06.024.
- Schilling, N., F. M. Neubauer, and J. Saur (2008), Influence of the internally induced magnetic field on the plasma interaction of Europa, *J. Geophys. Res.*, *113*, A03203, doi:10.1029/2007JA012842.
- Schunk, R. W. (1975), Transport equations for aeronomy, *Planet. Space Sci.*, *23*, 437–485.
- Schunk, R. W., and A. F. Nagy (2000), *Ionospheres: Physics, Plasma Physics, and Chemistry*, Cambridge Univ. Press, Cambridge U. K.
- Shematovich, V. I., R. E. Johnson, J. F. Cooper, and M. C. Wong (2005), Surface-bounded atmosphere of Europa, *Icarus*, *173*, 480–498, doi:10.1016/j.icarus.2004.08.013.
- Simon, S., J. Saur, H. Krieger, F. M. Neubauer, U. Motschmann, and M. K. Dougherty (2011), Influence of negatively charged plume grains and hemisphere coupling currents on the structure of Enceladus' Alfvén wings: Analytic modeling of Cassini magnetometer observations, *J. Geophys. Res.*, *116*, A04221, doi:10.1029/2010JA016338.
- Simon, S., J. Saur, S. C. van Treeck, H. Krieger, and M. K. Dougherty (2014), Discontinuities in the magnetic field near Enceladus, *Geophys. Res. Lett.*, *41*, 3359–3366, doi:10.1002/2014GL060081.
- Simon, S. (2015), An analytical model of sub-Alfvénic moon-plasma interactions with application to the hemisphere coupling effect, *J. Geophys. Res. Space Physics*, *120*, 7209–7227, doi:10.1002/2015JA021529.
- Sittler, E. C., and D. F. Strobel (1987), Io plasma torus electrons—Voyager 1, *J. Geophys. Res.*, *92*, 5741–5762, doi:10.1029/JA092iA06p05741.
- Sittler, E. C., et al. (2013), Plasma ion composition measurements for Europa, *Planet. Space Sci.*, *88*, 26–41, doi:10.1016/j.pss.2013.01.013.
- Southwood, D. J., M. G. Kivelson, R. J. Walker, and J. A. Slavin (1980), Io and its plasma environment, *J. Geophys. Res.*, *85*, 5959–5968, doi:10.1029/JA085iA11p05959.
- Southwood, D. J., and M. W. Dunlop (1984), Mass pickup in sub-Alfvénic plasma flow—A case study for Io, *Planet. Space Sci.*, *32*, 1079–1086.
- Spencer, J. R., et al. (2007), Io volcanism seen by New Horizons: A major eruption of the Tvashtar Volcano, *Science*, *318*, 240–243, doi:10.1126/science.1147621.
- Stone, J. M., and M. L. Norman (1992), ZEUS-2D: A radiation magnetohydrodynamics code for astrophysical flows in two space dimensions. I—The hydrodynamic algorithms and tests, *Astrophys. J. Suppl. Ser.*, *80*, 753–790, doi:10.1086/191680.
- Szegö, K., et al. (2000), Physics of mass loaded plasmas, *Space Sci. Rev.*, *94*, 429–671.
- Vasyliūnas, V. M. (2016), Physical origin of pickup currents, *Ann. Geophys.*, *34*, 153–156, doi:10.5194/angeo-34-153-2016.

- Volwerk, M., M. G. Kivelson, and K. K. Khurana (2001), Wave activity in Europa's wake: Implications for ion pickup, *J. Geophys. Res.*, *106*, 26,033–26,048, doi:10.1029/2000JA000347.
- Volwerk, M., K. Khurana, and M. Kivelson (2007), Europa's Alfvén wing: Shrinkage and displacement influenced by an induced magnetic field, *Ann. Geophys.*, *25*, 905–914, doi:10.5194/angeo-25-905-2007.
- Wolf-Gladrow, D. A., F. M. Neubauer, and M. Lussem (1987), Io's interaction with the plasma torus—A self-consistent model, *J. Geophys. Res.*, *92*, 9949–9961, doi:10.1029/JA092iA09p09949.
- Zimmer, C., K. K. Khurana, and M. G. Kivelson (2000), Subsurface oceans on Europa and Callisto: Constraints from Galileo magnetometer observations, *Icarus*, *147*, 329–347, doi:10.1006/icar.2000.6456.