<http://www.diva-portal.org>

This is the published version of a paper published in *Journal of Geophysical Research - Space Physics*.

Citation for the original published paper (version of record):

Lindkvist, J., Holmström, M., Khurana, K K., Fatemi, S., Barabash, S. (2015)
Callisto plasma interactions: Hybrid modeling including induction by a subsurface ocean.
Journal of Geophysical Research - Space Physics, 120(6): 4877-4889
<http://dx.doi.org/10.1002/2015JA021212>

Access to the published version may require subscription.

N.B. When citing this work, cite the original published paper.

Permanent link to this version:

<http://urn.kb.se/resolve?urn=urn:nbn:se:umu:diva-107178>

RESEARCH ARTICLE

10.1002/2015JA021212

Key Points:

- General morphology of the plasma interaction with Callisto using a hybrid model
- Comparison between the model and *Galileo* magnetic field observations
- Best fit with observations if induction from a subsurface ocean is included

Correspondence to:

J. Lindkvist,
jesper@irf.se

Citation:

Lindkvist, J., M. Holmström, K. K. Khurana, S. Fatemi, and S. Barabash (2015), Callisto plasma interactions: Hybrid modeling including induction by a subsurface ocean, *J. Geophys. Res. Space Physics*, 120, 4877–4889, doi:10.1002/2015JA021212.

Received 15 MAR 2015

Accepted 1 JUN 2015

Accepted article online 4 JUN 2015

Published online 30 Jun 2015

Callisto plasma interactions: Hybrid modeling including induction by a subsurface ocean

Jesper Lindkvist^{1,2}, Mats Holmström¹, Krishan K. Khurana³, Shahab Fatemi^{4,5}, and Stas Barabash¹
¹Swedish Institute of Space Physics, Kiruna, Sweden, ²Department of Physics, Umeå University, Umeå, Sweden,

³Department of Earth and Space Sciences, University of California, Los Angeles, California, USA, ⁴Space Sciences Laboratory, University of California, Berkeley, California, USA, ⁵Solar System Exploration Research Virtual Institute, NASA Ames Research Center, Moffett Field, California, USA

Abstract By using a hybrid plasma solver (ions as particles and electrons as a fluid), we have modeled the interaction between Callisto and Jupiter's magnetosphere for variable ambient plasma parameters. We compared the results with the magnetometer data from flybys (C3, C9, and C10) by the *Galileo* spacecraft. Modeling the interaction between Callisto and Jupiter's magnetosphere is important to establish the origin of the magnetic field perturbations observed by *Galileo* and thought to be related to a subsurface ocean. Using typical upstream magnetospheric plasma parameters and a magnetic dipole corresponding to the inductive response inside the moon, we show that the model results agree well with observations for the C3 and C9 flybys, but agrees poorly with the C10 flyby close to Callisto. The study does support the existence of a subsurface ocean at Callisto.

1. Introduction

Callisto, Jupiter's second largest satellite, is the outermost of the four Galilean moons. Callisto is located at a distance of $1.88 \cdot 10^6$ km ($\approx 27 r_J$) from Jupiter, where $r_J = 69.9 \cdot 10^3$ km is the mean radius of Jupiter. Callisto's radius is $r_C = 2410$ km. To a very good approximation Callisto is orbiting in the equatorial plane of Jupiter [Neubauer, 1999]. The rotation axis of Jupiter is tilted 9.6° with respect to the magnetic dipole axis of Jupiter [Khurana, 1997]. Because of the fast rotation of Jupiter compared to the orbital speed of Callisto, the magnetic field that Callisto encounters will change with a synodic period of 10.1 h [Kivelson et al., 1999]. During this period, the magnetospheric plasma that Callisto encounters will be much denser close to the magnetic equator than in the magnetic lobes [Kivelson et al., 2004]. The magnetospheric plasma is moving with almost corotational velocity (~ 200 km/s) at Callisto's orbit, while Callisto's orbital velocity is only ~ 8 km/s [Kivelson et al., 2004]. This means that the bulk of the magnetospheric plasma is hitting the trailing hemisphere of the moon in its orbit around Jupiter.

The magnetosphere's effect on Callisto's local plasma environment can be summarized to two coupled effects: first, the plasma processes close to Callisto, e.g., the currents in the ionosphere or Alfvén wings and second, the change of the external magnetic field in time (internally induced currents) [Saur et al., 2010].

To model the magnetospheric interaction with Callisto one needs to know the internal structure of the object to correctly model the induced response, but then again the information on the internal structure of solar system bodies can be constrained from magnetic field observations. The *Galileo* spacecraft made eight flybys of Callisto. During the *Galileo* prime mission the spacecraft had three flybys (C3, C9, and C10). Magnetic field perturbations associated with Callisto were observed during the flybys. These field perturbations have been interpreted as due to subsurface currents induced by the variable external dipole field of Jupiter [Khurana et al., 1998]. When a conductive body is immersed in a time-varying external field, currents will be induced in the body. The currents will generate a magnetic field that opposes the change in the external field (here Jupiter's magnetic field). The case of a spherical conductor in a vacuum, subject to a changing external field, can be investigated analytically. Such a model was applied to Callisto by Zimmer et al. [2000]. There, a simple representation of the electrical structure of the moon is adopted, with a spherical shell of uniform conductivity and zero conductivity elsewhere. Their analytical dipole model can explain C3 and C9 out of the first three flybys simultaneously [Kivelson et al., 1999]. The model implies that a subsurface ocean is required to explain the observations [Khurana et al., 1998]. The best fitted dipole for the C3 and C9 flybys was found to lie in the

Figure 1. Shown is the geometry of the first three Callisto flybys by *Galileo*. The circle represents Callisto. Jupiter is located to the right. The corotating plasma of Jupiter is flowing downward along the $+x$ axis and precipitate on Callisto's nightside, creating a plasma wake. The direction to the Sun during closest approach for the three different flybys is shown with yellow arrows. The trajectories of the three first *Galileo* flybys are illustrated by two black arrows each, where the closest approach is found where the first arrow ends and the second begins. Since the y and z coordinates depend on the direction of the external field, and hence the specific flyby, they are left out.

range $0.7 \leq A \leq 1.0$, $\phi = 0$ [Zimmer *et al.*, 2000], where A is the amplitude of the dipole response normalized to the variable external field and ϕ its phase lag.

The analytical model assumes a conductor in a vacuum. In reality, Jovian magnetospheric plasma is flowing past Callisto. This plasma flow, and the resulting currents in the plasma, will also contribute to any observed magnetic field disturbances observed near Callisto. In this work we use a model that includes the plasma flow and can thus quantify the contribution from the plasma flow.

The plasma flow passing Callisto is supersonic [Neubauer, 1998], creating a plasma wake. The flow is also sub-Alfvénic or almost sub-Alfvénic [Neubauer, 1998]. The interaction of a conducting object with a sub-Alfvénic plasma carrying frozen-in magnetic field perpendicular to the flow results in a structure called an Alfvén wing [Kivelson, 2000; Kivelson *et al.*, 2004]. In an Alfvén wing, the magnetic field will be slightly compressed on the ram side and the magnetic fields will drape around and through the object creating a relaxed (weaker) field in the plasma wake. The main topology is a winglike structure along the external magnetic field that have currents flowing along them.

An important thing to note is that a conductor in a moving plasma with a homogeneous magnetic field and a conductor in vacuum exposed to a time-varying external field are both increasing the magnitude of the magnetic field on their ram side. However, in the plasma wake the magnetic field magnitude will decrease for a conductor in a plasma since the magnetic field will diffuse slowly through the object and increase for a conductor in a time-varying external field (induced dipole) due to symmetry of the induced currents.

Additionally, Callisto has been observed to have an ionosphere when the subsolar and ram sides coincide (when the solar photons and magnetospheric plasma are coming from the same direction) [Kliore *et al.*, 2002]. The observations indicate that both plasma impact and photoionization are needed to create an ionosphere [Kliore *et al.*, 2002]. The ionosphere could for example be due to sputtered water and other molecules creating a neutral atmosphere, which accompanied by photoionization create the ionosphere. The angle between the solar photon flux and plasma flux should be less than 90° for a significant ionosphere to be present [Kliore *et al.*, 2002]. During an orbit around Jupiter (16.7 days) the ionospheric configuration of Callisto is thus expected to vary, since that is how long it takes for the subsolar and ram sides to coincide once again. The C3, C9, and C10 flybys of Callisto were all done when the Sun was on the opposite side of the plasma flow (for a geometric view, see Figure 1), i.e., in the morning local time of Jupiter's magnetosphere. Thus, a significant ionosphere is less likely during these flybys [Kliore *et al.*, 2002]. However, only the C9 flyby passed on the nightside of Callisto and could make an observation through solar occultation, and no significant ionosphere was observed [Kliore *et al.*, 2002].

The high plasma densities of the C3 and C10 flybys close to Callisto but not far in the wake suggests ionospheric plasma rather than plasma from Callisto being swept downstream [Gurnett *et al.*, 2000]. Also,

Khurana *et al.* [1997] see no indication of any intrinsic field in Callisto during the flybys by *Galileo*. The magnetic field perturbations should thus depend mainly on the induced currents inside Callisto (induced via plasma interactions and/or the time-varying magnetic field) and due to a possible ionosphere.

The goal of this article is to understand the magnetospheric interaction with Callisto and how Callisto affects its plasma environment using a hybrid code described in section 2. For studying the magnetospheric interaction with Callisto, one can view Jupiter as a magnetic field generator, and the volcanic innermost moon Io as the source of plasma constantly filling the Jovian magnetosphere. The magnetic field of Jupiter and the magnetospheric plasma parameters define the boundary conditions for the simulation box. Runs are made for different sets of parameters defining the plasma environment. We then present the results from the model in section 3. First, we present the general interaction between Callisto and the surrounding plasma, then we make specific comparisons with magnetic field observations during the first three *Galileo* flybys; C3, C9, and C10. In section 4 we discuss the results and their implications to our understanding of the magnetospheric interactions with satellites.

2. Model

We use a self-consistent hybrid plasma model [Holmström *et al.*, 2012] for the interaction between Callisto and the magnetospheric plasma of Jupiter. In the hybrid approximation, ions are treated as particles and electrons as a massless fluid. In the model description of section 2.1 we use SI units.

2.1. Model Description

The trajectory of an ion, $\mathbf{r}(t)$ and $\mathbf{v}(t)$, with charge q and mass m , is given by the solution of the equation of motion with the Lorentz force,

$$\frac{d\mathbf{r}}{dt} = \mathbf{v}, \quad \frac{d\mathbf{v}}{dt} = \frac{q}{m} (\mathbf{E} + \mathbf{v} \times \mathbf{B}),$$

where $\mathbf{E} = \mathbf{E}(\mathbf{r}, t)$ is the electric field, and $\mathbf{B} = \mathbf{B}(\mathbf{r}, t)$ is the magnetic field. The electric field is given by

$$\mathbf{E} = \frac{1}{\rho_i} (-\mathbf{J}_i \times \mathbf{B} + \mathbf{J} \times \mathbf{B} - \nabla p_e) + \eta \mathbf{J} - \eta_h \nabla^2 \mathbf{J}, \quad (1)$$

where the current density, $\mathbf{J} = \mu_0^{-1} \nabla \times \mathbf{B}$, ρ_i is the ion charge density, $\mathbf{J}_i$ is the ion current density, p_e is the electron pressure, η is the resistivity, and η_h is the hyperresistivity [Holmström, 2013]. Using hyperresistivity will diffuse high-frequency wave structures, while preserving lower frequency ones [Maron *et al.*, 2008].

The gradient of the electron pressure is calculated by imposing quasi-neutrality and an adiabatic index, γ . Then Faraday's law is used to advance the magnetic field in time,

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E}. \quad (2)$$

In vacuum regions, which are defined by the number density being less than a given value, $n < n_{\min}$, and inside the obstacle (Callisto here), we set $1/\rho_i = 0$ in equation (1), and this is reduced to solving the magnetic diffusion equation,

$$\frac{\partial \mathbf{B}}{\partial t} = \frac{\eta}{\mu_0} \nabla^2 \mathbf{B} + \eta_h \nabla \times \nabla^2 \mathbf{J}, \quad (3)$$

containing the extra term with hyperresistivity. This means that we can model arbitrary internal resistivities, that can vary with position [Holmström, 2013]. A constraint on the time step is being inferred since the field cannot diffuse more than one cell per time step,

$$\Delta t < \frac{\mu_0 (\Delta x)^2}{2\eta},$$

where Δt is the time step and Δx is the cell size. The time step is referred to as the discrete step in time for moving the particles (ions). The electromagnetic fields can be (if preferred) updated more frequently, so to say "subcycled," since it is at most times computationally cheap to update the fields compared to moving all the particles.

To make a fully self-consistent model of the Callisto plasma interaction, we would like to assume an internal resistivity profile for Callisto and then run the model with the external field (Jupiter's magnetospheric field) changing over time, as Callisto moves in its orbit. This is, however, computationally infeasible. We can only run the model on the order of minutes, even on a large computational cluster, and the timescale of the changing external field is on the order of hours. Also, the spatial resolution of the model makes it difficult to model, e.g., conducting shells with a thickness on the order of kilometers. Because of this, we choose a compromise. We assume Callisto to be a resistive body and add a magnetic dipole at the center of Callisto. This dipole field then represents all the subsurface currents, as is the case in the analytical model by *Zimmer et al.* [2000]. This approach will allow us to study details of the interaction between Callisto and the surrounding plasma in the order of minutes and, in particular, to quantify the contribution of plasma effects to observed magnetic field disturbances near Callisto. Just as in the analytical solution by *Zimmer et al.* [2000], the modeled dipole moment used here will be in the opposite direction of the variable part of the external field, referred to as "the primary field" and assumed to be constant in the model. The external field is varying over time, but its component along Jupiter's rotation axis is almost constant over time. By removing the constant component, we are left with the part that is responsible for the induction inside Callisto, i.e., the primary field.

Even with these simplification, modeling the plasma interactions of Callisto is computationally difficult. First, the plasma flow is sub-Alfvénic or almost sub-Alfvénic. Thus, waves will also propagate upstream. Boundary conditions are needed that allow upstream propagating waves to exit the computational domain without reflection. This could be handled by absorbing boundary conditions, but we here choose to use a periodic domain. This puts a limit on the running time of the simulation—when the solution starts to interact with itself through the periodic boundaries. To run for longer times, the solution domain needs to be enlarged. Second, the low plasma densities near Callisto puts severe restrictions on the time step to achieve numerical stability. This is because one stability restriction on the time step is proportional to the square of the ratio between the cell size and the ion inertial length, δ_i . This is given by the constraint [Pritchett, 2000]

$$\Omega_i \Delta t < \frac{(\Delta x / \delta_i)^2}{\sqrt{N\pi}},$$

where Ω_i is the ion cyclotron frequency, Δt is the time step, Δx is the cell size, and N is the spatial dimension.

2.2. Coordinate System and Simulation Box

The coordinate system we will use is called "Satellite Centered Phi-B Coordinates (SPhiB)". It is centered in the middle of Callisto. The +x axis is in the direction of the flow of plasma. The external magnetic field $\mathbf{B}$ is defined to be in the xz plane with its z component pointing toward -z, and the y axis completes the right-hand system. The convective electric field is given by $\mathbf{E}_0 = -\mathbf{u} \times \mathbf{B}_0$, where $\mathbf{u}$ is the plasma bulk velocity and $\mathbf{B}_0$ is the Jovian external magnetic field. Note that the convective electric field will, in this configuration, always be in the -y direction.

The simulation domain is divided into a Cartesian grid with cubic cells of the size $\Delta x = r_C/8$. The domain in x, y, and z ranges from $-9r_C$ to $9r_C$. We use 64 macro-particles per cell as initial condition and periodic boundary conditions. We assume 3 degrees of freedom for electrons when handling the gradient of the electron pressure, so the adiabatic index is set to $\gamma = 5/3$. We assume a vacuum resistivity of $\eta_v = 2.2 \cdot 10^6$ Ohm m, which is used when solving equation (3) for regions of a number density less than $n_{\min} = n_0/4$, where n_0 is the ambient plasma density. Assuming that the currents inside Callisto are due to the induced dipole, we can assume a resistive Callisto and set its resistivity equal to the highest resistivity in the model; i.e., the chosen vacuum resistivity, $\eta_C = \eta_v$, resulting in a magnetic Reynold's number of 0.1, when using a typical length equal to Callisto's radius. In the model, the high internal resistivity ensures that no extra currents will be induced inside Callisto, thus ensuring that the internal currents in the conductive subsurface ocean are represented by the specified magnetic dipole. The plasma resistivity and hyper resistivity which are nominally zero we set to $\eta = 4.4 \cdot 10^3$ Ohm m and $\eta_h = \eta \cdot (\Delta x)^2/2$, respectively. The plasma and hyper resistivities are set low enough to not significantly alter any physical wave in the simulation domain but will instead dampen numerical oscillations. In vacuum regions, and inside Callisto, the hyperresistivity term in equation (3) will be small compared to the magnetic diffusion term. To satisfy the limit of stability [Holmström, 2013] we use a time step of $\Delta t = 1.9 \cdot 10^{-2}$ s for moving the ions. Furthermore, the electromagnetic fields are updated 10 times for each time step (Δt).

Table 1. Parameters for the Plasma Environment Around Callisto for the “General Case” and “Low-Density Case”

Parameter	Denotation	Unit	General Case	Low-Density Case
External field	$\mathbf{B}_0$	nT	(0, 0, −35)	
Primary field	$\mathbf{B}_{\text{prim}}$	nT	(0, −10.45, −31.55)	
Ion number density	n_0	cm^{-3}	1.1	0.55
Plasma bulk velocity	u	km/s	175	
Mean particle mass	$\bar{m}_i$	amu	15	
Ion temperature	T_i	eV	200	
Electron temperature	T_e	eV	100	
Ion thermal gyroradius	r_g	km	230	
Gyration time	t_g	s	28	
Plasma beta	β		0.1	0.05
Sonic Mach number	M_S		3.1	
Alfvénic Mach number	M_A		0.93	0.66
Magnetosonic Mach number	M_{MS}		0.89	0.64

When the simulation is initiated, the ions (macro-particles) are evenly distributed everywhere outside Callisto, each with their own Maxwellian distribution. We do not consider any high-energy tail in our simulations. Since the density of the high-energy tail will be too low to affect the fields, one can consider them as independent test particles, and will therefore not affect the ion distribution considered here. Also, the magnetic field is homogeneous everywhere and equal to the given external field. Regarding conductive objects, this means that even though the estimated diffusion time of magnetic fields through Callisto is high, the time it takes to reach steady state might be small, due to the fact that the initial condition might be close to the steady state solution.

In the simulation itself two magnetic fields add together to give the total magnetic field. One is equal to the magnetic dipole, which is specified by a magnetic moment, $\mathbf{M}$, centered in the object given by magnitude and its direction; sim_m , sim_{mx} , sim_{my} , sim_{mz} . This field will be constant in the simulation because the actual physics with a time-varying field is not used here, as discussed previously. The other field is initially equal to the external field, $\mathbf{B}_0$, given in three components; sim_{bx} , sim_{by} , sim_{bz} . This field will change in time according to Faraday's law (equation (2)). The magnetic dipole is modeled with a magnetic moment at the center of Callisto given by [Saur et al., 2010]:

$$\mathbf{M} = -\frac{4\pi}{\mu_0} \mathbf{A} \mathbf{B}_{\text{prim}} r_C^3 / 2,$$

where $\mathbf{B}_{\text{prim}}$ is the primary field, r_C is Callisto's radius, and A is the normalized dipole strength: $0 \leq A < (r_0/r_C)^3$ [Zimmer et al., 2000], where r_0 is the outer radius of the conducting subsurface ocean.

As Jupiter rotates, the magnetic field experienced by Callisto will consist of a constant magnetic field in the direction opposite of Jupiter's rotation axis. The other component (the primary field), which almost lies in the

Table 2. Parameters for the Plasma Environment Around Callisto for the “Comparison Cases”

Parameter	Denotation	Unit	Case C3	Case C9	Case C10
External field	$\mathbf{B}_0$	nT	(−2.4, 0.0, −33.5)	(1.7, 0.0, −35.3)	(−1.05, 0.0, −30.8)
Primary field	$\mathbf{B}_{\text{prim}}$	nT	(−3.4, −10.5, −31.7)	(5.8, 8.45, −32.9)	(−1.05, 10.2, −26.95)
Gyration time	t_g	s	29	28	32
Alfvénic Mach number	M_A		0.97	0.92	1.06
M-sonic Mach number	M_{MS}		0.93	0.88	1.00
UT at closest approach	$t_{C/A}$		11/04/1996 ^a 13:34	06/25/1997 ^a 13:48	09/17/1997 ^a 00:19
Altitude at C/A	C/A	km	1138.9	421.0	538.3
Magnetic latitude	λ	deg	7.1	−7.8	−6.9

^aDates are formatted as month/day/year.

Figure 2. Plots from $x = -1$ (surface) to $x = -6$ (upstream) at $y = z = 0$ of the magnetic field magnitude, $|B|$, the ion velocity magnitude, v_I , and the ion number density, n_I , for the General Case. The magnetospheric plasma is traveling in the $+x$ direction, and the external magnetic field is pointing in the $-z$ direction with a magnitude of 35 nT. The horizontal axis is given in Callisto radii (r_C). The vertical axis is given in values normalized to the parameters' ambient values. The vertical black solid line marks the region where interpolation breaks down due to cell size for quantities that are not possible to extrapolate through the surface of the object, such as density and velocity.

orbital plane of Callisto, is the one that varies with the synodic period of 10.1 h, and is responsible for the magnetic induction in Callisto.

Note that the results presented in section 3 do not show the full simulated domain. Since we have periodic boundary conditions, we do not show parts of the simulation domain which have not reached steady state. The steady state region is chosen to be where more than 70% of the ambient plasma starting at Callisto ($x = 0$) at time zero has passed the steady state region boundary downstream, and less than 3% has emerged back into the steady state region upstream through the periodic boundary of the simulation domain. Also, fictive

Figure 3. The magnitude of the magnetic field perturbation due to plasma effects together with the background field in nT, which is the same as the magnitude of the total magnetic field subtracting the dipole field. (right) The General Case and (left) the Low-Density Case. The magnetospheric plasma is traveling in the $+x$ direction, the external magnetic field is pointing in the $-z$ direction with a magnitude of 35 nT. The black circles represent Callisto. The axes are given in Callisto radii (r_C).

Figure 4. The B_x component of the total magnetic field (nT) for the General Case. The magnetospheric plasma is traveling in the $+x$ direction, the external magnetic field is pointing in the $-z$ direction with a magnitude of 35 nT. The black circle represents Callisto. The axes are given in Callisto radii (r_C).

Alfvén and magnetosonic waves created at Callisto's center at time zero have reached but not yet emerged back into the steady state region through the periodic boundary of the simulation domain.

2.3. Model Parameters

Callisto encounters various kinds of plasma environments in its orbit around Jupiter. Typical or mean values have been presented by Neubauer [1998] and Kivelson *et al.* [2004]. Since different values are given by these authors, we choose to expand our study into different cases. In each simulation, the ambient values remain constant over time.

Figure 5. The current density in A m^{-2} for the General Case. (left) The J_y component of the current density of a cut through $y = 0$. (right) The J_z component of a cut in the plasma wake at $x = 2 r_C$. The current density inside Callisto is zero since the currents responsible for creating the magnetic dipole are not included here. The magnetospheric plasma is traveling in the $+x$ direction and the external magnetic field is pointing in the $-z$ direction. The black circles represent Callisto. The axes are given in Callisto radii (r_C). The maximum of the color bar represent the ambient ion current density magnitude for the General Case, $|J_{i,0}| = 3.08 \cdot 10^{-8} \text{ A m}^{-2}$.

Figure 6. (top and bottom rows) The ion number density in cm^{-3} for the General Case for several different cuts. The magnetospheric plasma is traveling in the $+x$ direction, and the external magnetic field is pointing in the $-z$ direction. The ambient ion number density is $n_0 = 1.1 \text{ cm}^{-3}$. The black circles represent Callisto. The axes are given in Callisto radii (r_C). Figure 6 (bottom right) shows a contour where every contour line represents an $n_0/8 \approx 0.14 \text{ cm}^{-3}$ change.

We use the values for the plasma parameters given by Neubauer [1998], which we call the “General Case,” with number density $n_0 = 1.1 \text{ cm}^{-3}$. However, to also account for the much lower ambient number density given by Kivelson *et al.* [2004], we decrease the number density to include a case we call “Low-Density Case” with number density $n_0 = 0.55 \text{ cm}^{-3}$. Further, for comparison with flybys, we use the observed magnetic field data measured by the MAG instrument onboard *Galileo*. These we call “Comparison Cases,” which all have been modeled with the same two sets of number densities as above.

The external magnetic field changes slightly during a flyby, but we choose to make only one simulation with the field estimated at the closest approach of Callisto by *Galileo*. More accurate would be to run a simulation for each external field experienced during a flyby, but this is computationally expensive.

2.3.1. General Case and Low-Density Case

To model the general plasma interaction similar to the *Galileo* flybys C3, C9, and C10, we have used typical plasma parameters of the Jovian magnetospheric plasma at the orbit of Callisto [Neubauer, 1998]. A dipole within the range of the best fitted dipole from the C3 and C9 flybys [Zimmer *et al.*, 2000] is included with a dipole strength $A = 0.85$ and phase lag $\phi = 0$. This dipole strength corresponds to a subsurface ocean at a depth not greater than 130 km.

During the C3, C9, and C10 flybys, the ionosphere is assumed to be nonexistent since the solar photon flux and magnetospheric plasma flux are antiparallel. The angle between these fluxes should be less than 90° for a significant ionosphere to be present [Kliore *et al.*, 2002].

The external magnetic field is around $B_0 = 35 \text{ nT}$ [Neubauer, 1998], which we set to $\mathbf{B}_0 = (0, 0, -35) \text{ nT}$. From *Galileo* data, one can estimate the primary field $\mathbf{B}_{\text{prim}}$ from the equatorial projection of the external field during the C3, C9, and C10 flybys. The angle between the primary field, $\mathbf{B}_{\text{prim}}$, and the external field, $\mathbf{B}_0$, is $\pm 18^\circ$ for these flybys. For this General Case, we use the projection of the C3 flyby: $\mathbf{B}_{\text{prim}} = (0, -10.45, -31.55) \text{ nT}$.

The simulation ions are positively singly charged with a mass of $\bar{m} = 15 \text{ amu}$, which is equal to the mean mass of the magnetospheric ions at Callisto’s orbit. We do not take into account the various species of ions and charge states that exist in the Jovian magnetosphere and instead use one species with the mean mass of the magnetospheric ions. The magnetospheric plasma is moving with the speed $u = 175 \text{ km/s}$ along the

Figure 7. A spherical shell cut at an altitude of 130 km for the General Case with the cell size $dx = r_C/16$. Zero longitude/latitude corresponds to the center of the trailing hemisphere; i.e., where the magnetospheric plasma is flowing straight into the surface, the external magnetic field is pointing downward, and the convective electric field is pointing to the right. The white circles correspond to the direction of the Sun, and the black circles correspond to the direction of Jupiter. (top) The ion number density relative to its ambient value. (bottom) The mean ion flux toward the surface relative to the mean ion flux magnitude of the undisturbed magnetospheric plasma.

+x direction. The ion distribution is assumed to be Maxwellian with the temperature $T_i = 200$ eV. The electron fluid has the temperature $T_e = 100$ eV, which is used to calculate the gradient of the pressure term for the electric field in equation (1). The Low-Density Case uses the same parameters as the General Case but with a lower ambient number density. See Table 1 for a complete summary of parameters used for these cases.

2.3.2. Comparison Cases: C3, C9, C10

The C3, C9, and C10 flybys by *Galileo* were all done when the solar photons and magnetospheric plasma came from opposite directions. In this scenario, a significant ionosphere is not expected [Kliore *et al.*, 2002]. The C3 and C10 flybys went through the plasma wake on the sunlit side of Callisto, while the C9 flyby went upstream of the plasma flow and could therefore make an observation through solar occultation and observed no significant ionosphere [Kliore *et al.*, 2002]. A geometric view can be seen in Figure 1.

We used the following assumptions on the magnetic field for our simulations for the comparison with the magnetometer data: For the flybys C3 and C9, the external field and the primary field were taken from Zimmer *et al.* [2000], where the primary field is estimated from the model by Khurana [1997]. For C10, the external field was estimated from *Galileo* measurements and the primary field estimated from the equatorial projection of the external field at closest approach.

The external and primary fields are summarized in Table 2.

3. Model Results

We now present the model results for the different cases described in the previous section. All simulation results are shown when the solution has reached a steady state. For this we choose a simulation time of 110 s for the given domain. The simulation results include both magnetospheric plasma and a magnetic dipole.

3.1. General Case and Low-Density Case

Since the interaction is supersonic, but sub-Alfvénic, we make a line plot from the center of Callisto toward the incoming plasma as shown in Figure 2 for the General Case. The ion number density, ion speed, and magnetic field magnitude change continuously with distance. No shock upstream of the flow is formed due to the relatively low conductivity of the obstacle.

Figure 8. Comparison of magnetic field observations and simulations during the C3 flyby with time in UT on 4 November 1996. Shown are the different magnetic field components and magnitude. The black vertical line indicates the time of closest approach, and the green vertical lines indicate the crossing of the geometrical projection of Callisto's orbit on Jupiter's equatorial plane. The magnetometer data from *Galileo* is shown as a black solid line, the modeled dipole as a green solid line, the simulation results as a red solid line for the General Case, and a blue solid line for the Low-Density Case.

Figure 9. Comparison of magnetic field observations and simulations during the C9 flyby with time in UT on 25 June 1997. Shown are the different magnetic field components and magnitude. The black vertical line indicates the time of closest approach, and the green vertical lines indicate the crossing of the geometrical projection of Callisto's orbit on Jupiter's equatorial plane. The magnetometer data from *Galileo* is shown as a black solid line, the modeled dipole as a green solid line, the simulation results as a red solid line for the General Case, and a blue solid line for the Low-Density Case.

Figure 10. Comparison of magnetic field observations and simulations during the C10 flyby with time in UT on 16 September 1997. Shown are the different magnetic field components and magnitude. The black vertical line indicates the time of closest approach, and the green vertical lines indicate the crossing of the geometrical projection of Callisto's orbit on Jupiter's equatorial plane. The magnetometer data from *Galileo* is shown as a black solid line, the modeled dipole as a green solid line, the simulation results as a red solid line for the General Case, and a blue solid line for the Low-Density Case.

Upstream of the flow, there is, however, a pileup of the magnetic field for both the General Case and the Low-Density Case due to the presence of the induced magnetic dipole. If one subtracts the magnetic field of the induced dipole from the total magnetic field, one will have only the plasma-induced magnetic fields and the background field left. This magnetic field is shown in Figure 3. A high particle pressure as in the General Case will significantly perturb the magnetic fields. The Low-Density Case behaves as an induced magnetic dipole, and the plasma is almost not affecting its environment at all.

The magnetic field is draping around Callisto in the form of Alfvén wings. This can be seen in the $\mathbf{B}_x$ component in Figure 4, but these wings start farther downstream, compared to a nondipole case [Kivelson *et al.*, 2004].

The plasma interaction with Callisto leads to a significant anisotropy in the Alfvén wing current densities, as can be seen in Figure 5. These are not the typical Alfvén currents discussed by Kivelson [2000], where currents are flowing in the Alfvén wings to Callisto (J_z), and then goes through and across the object (J_y) in the direction of the convective electric field ($-y$), and finally back in the Alfvén wings (J_z) where the current then closes far from Callisto. Here additionally, there is a current flowing opposite of the convective electric field ($+y$). The magnetic field which is draping around Callisto in the form of Alfvén wings, combined with the presence of the dipole field create the magnetic configuration that gives a current in the $+y$ direction, J_y (see $\partial B_x / \partial z$ in Figure 4).

The draping and compression of the magnetic field around Callisto will in turn affect the upstream magnetic field and plasma since the flow is both sub-Alfvénic and submagnetosonic for both cases, effects that are not seen for an isolator in a supersonic flow (e.g., the Moon). The Alfvén wing currents develop when the plasma flow slows down because of the presence of a conducting object. Perturbations along the magnetic field propagate at the Alfvén speed while they are convecting downstream at the flow speed, u . The front created is tilted at an angle $\theta_A = \arctan(M_A)$ [Kivelson, 2000].

There is also an asymmetry in the Alfvén wings which is easier to see when looking at the ion number density in the upper right panel of Figure 6.

When closing in on Callisto with a sub-Alfvénic speed, the bulk ions will be slowed down and both precipitate and stream around Callisto. In the region where the total magnetic field is close to zero the ions speed up to

conserve the total pressure balance, keeping the ion flux constant. This creates two additional wakes seen in the number density close to Callisto in Figure 6 (bottom left).

The central plasma wake seems to be made out of two smaller wakes, seen in the number density of Figure 6 (bottom right). This is an ion kinetic effect which has also been seen for Europa by *Lipatov et al.* [2013] and cannot be seen in MHD models. The increase of number density that splits the wake in the middle can be seen in the precipitation map in Figure 7 (top), where a simulation of the General Case has been done with a cell size of $\Delta x = r_C/16$ to increase resolution. Farther downstream, in the central wake, one sees the wake expanding along the magnetic field as the magnetic field gradually returns to its ambient state.

The mean ion flux is shown in Figure 7 (bottom) and is showing the backflow of plasma from the wake to the surface of Callisto.

3.2. Comparison Cases

Here we compare the magnetic field configurations measured during the C3, C9, and C10 flybys with the magnetic fields from the model. The modeled fields include simulations of the General Case and Low-Density Case and a modeled dipole in vacuum. The effects of currents in the plasma can thus be seen as the magnetic field difference from the modeled dipole. The C3 flyby which passes through the plasma wake in Figure 8 fits best for the Low-Density Case, which is almost the same as the modeled dipole. The C9 flyby passing upstream of the plasma flow seen in Figure 9 fits best for the General Case. This should be due to the fact that a higher ambient density of plasma was present during the C9 flyby, while at the C3 flyby the dipole itself seems the better fit which indicates a lower ambient plasma density. The magnetic field during the C10 flyby passing through the plasma wake in Figure 10 differs greatly between model and observations for all cases.

4. Discussion

One assumption for using a dipole as a representation of the internal currents of Callisto is that $\nabla \times \mathbf{B} = 0$ in the plasma outside Callisto [*Saur et al.*, 2010]. The induced currents in the plasma by a conducting Callisto are proportional to the ambient ion number density, and a lower ambient ion number density makes the dipole approximation more valid.

No significant ionosphere was observed during the C9 flyby, but it cannot be said for certain if that is the case for the C3 and C10 flybys, since no solar occultation measurements were made on those flybys. According to *Kliore et al.* [2002] there should not be a significant ionosphere when the solar photons and magnetospheric plasma are not coming from within 90° of the same direction, which is the case for all these flybys. However, the C3 and C10 flybys passed on the sunlit side of Callisto, and plasma wave measurements estimated electron densities of up to 100 cm^{-3} for the C3 flyby [*Gurnett et al.*, 1997] and electron densities of up to 400 cm^{-3} for the C10 flyby [*Gurnett et al.*, 2000] at the central wake. A locally (but not globally) significant ionosphere might explain why the magnetometer data of the C3 and C10 flybys are more variable than the C9 flyby and why the perturbation is localized to the vicinity of Callisto, when the flyby is closest. The closest approach of the C3 flyby is about double that of the C10 flyby, at 1139 km and 538 km above the surface, respectively, which is why a local ionosphere would affect the magnetic fields during the C10 flyby more. If one assumes that the C3 and C10 flybys are passing through the same ionosphere, an approximate electron scale height can be deduced to be $H_e = 433 \text{ km}$. That is consistent with a scale height that is significantly higher at high altitudes [*Liang et al.*, 2005], compared to the scale height around 50 km: $H = 30 \text{ km}$ [*Liang et al.*, 2005]. If one further assumes that the scale height increases linearly with height, one can deduce an upper limit of the electron number density of $n_e = 3.7 \cdot 10^4 \text{ cm}^{-3}$ at the altitude of 50 km, which is consistent with observations of an ionosphere at Callisto by *Kliore et al.* [2002]. If the high electron densities during the C3 and C10 flybys are due to an ionosphere, it is rather suggested that a local ionosphere is always present close to the subsolar point, and its extent to higher solar zenith angles is proportional to how much plasma impacts that area on Callisto's surface. Precipitation on the dayside (in the wake) of Callisto can be seen for the General Case in Figure 7 and might give rise to a local ionosphere, which in turn explains the high plasma densities observed by *Gurnett et al.* [1997, 2000]. An ionospheric model for Callisto using data from the *Galileo* spacecraft is available [*Liang et al.*, 2005] and will be adopted for future work.

A broader peak around the closest approach of the C9 flyby by *Galileo* for the magnetic field would indicate that the plasma effects dominate over induction effects. However, the shape of the peak rather suggests more induction effects, i.e., lower plasma density. The flybys discussed have all been in regions of the magnetic lobes

of Jupiter, where the plasma densities are lower. Plasma wave measurements during the C10 flyby indicated an ambient electron number density of lower than $5 \cdot 10^{-2} \text{ cm}^{-3}$. In the magnetic equatorial regions, however, where the number density reaches values discussed in the General Case, the plasma effects can no longer be neglected.

When using the magnetic dipole suggested by Zimmer *et al.* [2000] it is important to note that our model which includes both a magnetic dipole and magnetospheric plasma, in contrast to vacuum, supports the notion of subsurface oceans at Callisto.

5. Conclusion

Currents induced in the Callisto body by the plasma flow carrying frozen-in magnetic field can lead to significant global effects and need to be considered in addition to currents induced by the external dipole field of Jupiter. A model including a magnetic dipole with an amplitude of $A = 0.85$ and without phase lag, within the range of the best fit by Zimmer *et al.* [2000], together with magnetospheric plasma can explain the interaction for the C3 and C9 flybys of Callisto. The study thus supports the existence of subsurface oceans at Callisto. To compare with and explain other flybys a complete model that includes plasma flow, external field change, and an ionosphere is needed. The plasma environment of Callisto provides the understanding of the fundamental processes taking place when a conductive object is immersed in a sub-Alfvénic flow of plasma.

References

- Gurnett, D. A., W. S. Kurth, A. Roux, and S. J. Bolton (1997), Absence of a magnetic-field signature in plasma-wave observations at Callisto, *Nature*, **387**, 261–262.
- Gurnett, D. A., A. M. Persoon, W. S. Kurth, A. Roux, and S. J. Bolton (2000), Plasma densities in the vicinity of Callisto from Galileo plasma wave observations, *Geophys. Res. Lett.*, **27**(13), 1867–1870.
- Holmström, M. (2013), Handling vacuum regions in a hybrid plasma solver, in *Numerical Modeling of Space Plasma Flows*, ASP Conf. Ser., vol. 474, pp. 202–207, Astron. Soc. of the Pacific, San Francisco, Calif.
- Holmström, M., S. Fatemi, Y. Futaana, and H. Nilsson (2012), The interaction between the Moon and the solar wind, *Earth Planets Space*, **64**, 237–245.
- Khurana, K. K. (1997), Euler potential models of Jupiter's magnetospheric field, *J. Geophys. Res.*, **102**(A6), 11,295–11,306.
- Khurana, K. K., M. G. Kivelson, C. T. Russell, R. J. Walker, and D. J. Southwood (1997), Absence of an internal magnetic field at Callisto, *Nature*, **387**(6630), 262–264.
- 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**(6704), 777–780.
- Kivelson, M. G. (2000), Currents and flows in distant magnetospheres, in *Magnetospheric Current Systems*, *Geophys. Monogr. Ser.*, vol. 118, edited by S. Ohtani *et al.*, pp. 339–352, AGU, Washington, D. C.
- 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**(A3), 4609–4625.
- 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*, edited by F. Bagenal, T. E. Dowling, and W. B. McKinnon, pp. 513–536, Cambridge Univ. Press, Cambridge, U. K.
- Kliore, A. J., A. Anabtawi, R. G. Herrera, S. W. Asmar, A. F. Nagy, D. P. Hinson, and F. M. Flasar (2002), Ionosphere of Callisto from Galileo radio occultation observations, *J. Geophys. Res.*, **107**(A11), 1407, doi:10.1029/2002JA009365.
- Liang, M.-C., B. F. Lane, R. T. Pappalardo, M. Allen, and Y. L. Yung (2005), Atmosphere of Callisto, *J. Geophys. Res.*, **110**, E02003, doi:10.1029/2004JE002322.
- Lipatov, A. S., J. F. Cooper, W. R. Paterson, E. C. Sittler Jr., 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.
- Maron, J. L., M.-M. M. Low, and J. S. Oishi (2008), A constrained-transport magnetohydrodynamics algorithm with near-spectral resolution, *Astrophys. J.*, **677**, 520–529.
- Neubauer, F. M. (1998), The sub-Alfvénic interaction of the Galilean satellites with the Jovian magnetosphere, *J. Geophys. Res.*, **103**(E9), 19,843–19,866.
- Neubauer, F. M. (1999), Alfvén wings and electromagnetic induction in the interiors: Europa and Callisto, *J. Geophys. Res.*, **104**(A12), 28,671–28,684.
- Pritchett, P. L. (2000), Particle-in-cell simulations of magnetosphere electrodynamics, *IEEE Trans. Plasma Sci.*, **28**, 1976–1990.
- Saur, J., F. M. Neubauer, and K.-H. Glassmeier (2010), Induced magnetic fields in solar system bodies, *Space Sci. Rev.*, **152**, 391–421.
- 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.

Acknowledgments

This research was conducted using resources provided by the Swedish National Infrastructure for Computing (SNIC) at the High Performance Computing Center North (HPC2N), Umeå University, Sweden. The software used in this work was in part developed by the DOE NNSA-ASC OASCR Flash Center at the University of Chicago. The hybrid solver is part of the openly available FLASH code and can be downloaded from <http://flash.uchicago.edu/>. The simulation results are available from the corresponding author on request. MAG data from the Galileo orbiter is publicly available via the NASA Planetary Data System (PDS) archive. Jesper Lindkvist is funded by the Swedish National Space Board (SNSB).

Michael Liemohn thanks two anonymous reviewers for their assistance in evaluating this paper.