Interaction of the Galilean Moons with their plasma environments

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Abstract

The Galilean moons, especially Io, affect not just their local environment but also the jovian ionosphere at the ends of the flux tubes connected to the moons. Moreover, the mass added to the magnetosphere by Io affects much of the rest of the magnetosphere. The magnetosphere is energized by this mass-loading, powering the aurora, accelerating radiation belt particles, and generating radio emissions. This review examines how the mass-loading affects the magnetosphere and ionosphere; the differences in the interactions of Io, Europa, Ganymede and Callisto; and some of the kinetic phenomena associated with the interaction.

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1. Introduction

The study of the jovian magnetospheres is almost as old as the study of the terrestrial magnetosphere. In 1955 radio emissions were discovered coming from Jupiter (Burke and Franklin, 1955) and quickly interpreted as signaling an immense jovian magnetosphere containing an intense radiation belt. It was not long afterward that Jupiter itself was subject to in situ investigations by Pioneer 10 and 11 and by Voyager 1 and 2. The discovery that Io controlled the occurrence of decametric radio emissions led to the first suggestions that Io interacted with its plasma environment (Piddington and Drake, 1968; Goldreich and Lynden-Bell, 1969). Today, in addition to the probing of this system by Pioneer, Voyager, and later Ulysses and Galileo, we have optical observations from IAU that dramatically illustrate the control of auroral emissions by the Galilean moons. Fig. 1 shows a composite picture of Jupiter, Io, Europa and Ganymede, the northern hemisphere aurora and the coupling of the moons to the ionosphere by the magnetic flux tubes that pass through them (Clarke et al., 2002). It is worth dwelling on this extremely informative diagram.

The moon on the left is Io at 5.9 jovian radii from the center of Jupiter. The inset shows more clearly the auroral spot and trailing emission associated with this moon. The spot is significantly larger than the flux tube crossing Io's geosynchronous cross section signifying a region of interaction surrounding Io that is much larger than the body. The auroral emission marks the region in which stress is applied from the ionosphere to the magnetosphere to accelerate plasma that initially has the orbital velocity of Io, to the velocity of the corotating magnetospheric plasma in the torus region. The emission marks the region where corotation is not occurring in the magnetosphere so magnetic flux tubes are slipping with respect to the ionosphere. Clearly, some distance (behind Io) is required to accelerate the newly added iogenic plasma.

Two weaker spots are seen at the foot-points of Europa and Ganymede. The Europa foot-point is not as bright as that of Ganymede, and is much less bright than that of Io. This agrees with the estimates of a much lower mass-loading rate at Europa than Io. Ganymede's interaction though does not signal the effect of mass-loading, rather a different interaction, one of two interacting magnetospheres, Jupiter's and Ganymede's.
as we describe in much more detail in a later section of this report.

These auroral spots and the auroral trail form but a small portion of the aura. As seen here over the northern polar cap, there is an entire oval of auroral emissions surrounding the polar regions. The oval, though not symmetric, on the dark side of the magnetosphere the aura erodes further into the tail. What is the source of these auroras? While not the proximate cause of the aura, the moons, and predominantly Io, are the ultimate cause. The mass-loaded plasma is slowly drifting outward and, because it is collisionless plasma, we may consider the magnetic flux tubes on which the plasma resides to also be carried outward with the plasma. The Ioospheric ionosphere that rotates with the planet fast to decelerate this plasma to corotational velocities just as it does near the moons. The reason this is necessary is that, if only the angular momentum imparted near the moons was available as the plasma moved outward, the plasma would move down because of the conservation of angular momentum. Here the auroral forms again mark the regions of ionospheric stress.

We cannot see the jovian magnetosphere in this picture. We can only see the places where specific flux tubes enter the ionosphere and upper atmosphere, near the visible cloud tops. If we could see the magnetosphere, it would be bullet-shaped with the round end of the bullet toward the Sun, the near side of Fig. 1, a picture taken from 1 AU, much closer to the Sun. The back end of the bullet, the tail of the magnetosphere, extends away from the Sun. Thus flux tubes that are corotating with Jupiter have difficulty expanding outward on the dayside of the planet. The outflow is stopped by the solar wind interaction, but as the planet turns toward dusk, these flux tubes can begin to move outward. When they do, the footprints of these expanded tubes move closer to the poles and again, because of conservation of angular momentum, must slow down further. In Fig. 1 the dusk aurora (on the right-hand side) are clearly displaced poloidally as expected. They are also much more structured and irregular than the morning aurora. This suggests that outward convection is episodic and not uniform.

Eventually, the plasma on the most poleward field lines must get dumped down the magnetotail. As discussed below this can be accomplished via the process known as reconnection. Expanded flux tubes should rapidly adjust their angular velocities to that of corotation and not cause aurora. Perhaps the rather uniform dark part of the dawn polar cap consists of closed, empty flux tubes.

Remote sensing of a system such as the auroral view shown in Fig. 1 is very instructive as it gives us an overview of the system and its interconnectivity. Nevertheless, we need in situ observations within the system to fully understand the processes that control the physics of the system. Fortunately, the Galileo spacecraft has provided almost eight years of data in the jovian magnetosphere to allow us to gain some understanding of how these processes work.

2. Io

There are three major ways that the Galilean moons affect their plasma environments. There is the addition of mass to the rotating magnetosphere, mostly productively from their tenuous atmospheres. There are the magnetic fields arising from electromagnetic induction in the electrically conducting interiors and there are magnetic fields due to dynamo processes. A third example of the effects of mass-loading, albeit the effects of mass-loading at Europa are significant and of some interest. Callisto appears to be the best example of the effects of electromagnetic induction but Europa is the more prominent example. Finally, Ganymede is by far the largest and thus far only clearly detectable intrinsic magnetic field. To review these diverse interactions we proceed to examine each of the Galilean moons in turn but will concentrate on the mode of interaction of which they are the epitome. For Io we concentrate on mass-loading process and electromagnetically coupling to the ionosphere. We do not cover the attempts to measure any intrinsic magnetic field or induction that have thus far been unsuccessful.
2.1. Electric potential drop

In a collisionless plasma, electrons can move quickly along a magnetic field line to remove any charge imbalance that may cause an electric field along the flux tube. Thus unless a flux tube is actively increasing or decreasing its bending angle, it is expected to have a constant electric potential along its length (except perhaps near the atmosphere where slippage can occur associated with the auroral acceleration and the consequent auroral luminosity).

Across a magnetic field line there is a frame-dependent electric field proportional to the vector cross product of the velocity of the plasma and the magnetic field, \( E = \mathbf{v} \times \mathbf{B} \) in SI units. For example, the torus plasma at the orbit of Io corotates with Jupiter at a velocity of 74 km/s while Io orbits at 17 km/s so that the relative velocity of the plasma and Io is 57 km/s. If the plasma ran into Io and was absorbed (with no deflection of the plasma) there would be a potential drop of 57,000 m/s \( \times \) \( 2 \times 10^{-3} \) T \( \times \) \( 2 \times 1.83 \times 10^6 \) m (\( = 417 \) kV) across Io. If there were no electrically conducting path across Io, no current would flow in response to this potential drop. This situation occurs at the Earth’s moon when it is in the solar wind as sketched in right-hand panel of Fig. 2.

If Io were a superconductor that excluded the jovian magnetic field threading the flowing plasma, then the plasma would flow around Io and the streamlining heading toward the center of Io would split. Across the infinitesimal width of this streamline there is no potential drop. Thus there would be no potential drop across Io. This situation occurs at Venus in the solar wind as illustrated in Fig. 2 where the Venus ionosphere generally acts as a superconductor on the time scale of mmoral fluctuations in the interplanetary magnetic field.

Since the jovian magnetic field at Io is rather steady except for the variation experienced due to the rotation of Jupiter’s tilted dipole past Io and since Io’s ionosphere should not exclude this steady field we might expect, at first, that a potential drop could arise, one that acted as a battery, or as it has been called a unipolar dynamo, that drove currents into (and out of) the ionosphere. This unipolar dynamo as shown in Fig. 3 could lead to radio emissions and explain the observed control of decametric radio emissions by Io (Piddington and Drake, 1968; Goldreich and Lynden-Bell, 1969).

For many years this mechanism was believed to be responsible for these emissions.

Voyager 1 provided the first indication that there was another possible mechanism when it measured the density of the Io torus (Bagastal, 1994). Io was providing approximately a ton of ions to the jovian magnetosphere a second (e.g., Bagastal et al., 1983). However, it was not appreciated at the time that this mass-loading process itself was sufficient to act as a barrier to the incoming flow. Galileo observations clearly showed the flow deflection (Frank et al., 1996). The added mass slowed the flow close to Io while the upper part of the flux tube was swept past Io. The beading of the mass-loaded flux tubes relative to more distant unloaded
circular flux tubes led to field-aligned currents. Thus, the spirit of Fig. 3 was achieved even though the currents were due to a different process. Important consequences of the mass-loading process are that the interaction region is much larger than an Io diameter and that the region of field-aligned current extends downstream from Io a long way (not just an Io diameter) because of the finite and slow rate of acceleration of the newly formed plasma.

It has been popular to describe the behavior of the flow of plasma near Io in terms of an Alfvén wing. Flux tubes that are convected from the torus into interaction with Io, slow down and the neighboring flux tubes must flow around them. The flux tube that penetrates Io bends at an angle given by the Alfvén Mach number, the velocity of the corotational velocity relative to Io divided by the Alfvén velocity. The Alfvén velocity is \( V_A(p) = \frac{B}{\sqrt{\mu_0 \rho}} \), where \( B \) is the magnetic field strength and \( \rho \) is the mass density, depends on the local mass density but is of the order of 200 km/s along the magnetic field. The torus plasma moves at \( \frac{V_A}{2} \) relative to Io. Thus the Alfvén wing should be tilted approximately 17°, sin \( \frac{\theta}{200} \) away from the vertical as sketched in Fig. 4. Linker et al. (1998, 1999, 1998b) Saar et al. (1999) and Saar and Saar (2000) have modeled this Alfvén-wing interaction with MHD codes. However, in these codes mass-loading can only be treated in an empirical manner and kinetic effects are not at all.

Mass-loading complicates this picture, as does the kinetic nature of the plasma. Since most torus plasma approaching Io is deflected around Io, plasma only slowly enters, crosses, and exits from the Io flux tube. If plasma is deflected by Io there must be a pressure gradient in the flow upstream from Io. At Io, unlike at Venus used in the previous example, the flow is sub-Alfvénic. That is, the flow is slower than the speed of the fast, compressional magnetosonic wave, a wave that moves at the square root of the sum of the squares of the Alfvén and sound speeds when moving perpendicular to the magnetic field. Thus, the situation resembles that shown in the upper panel of Fig. 5 rather than the lower panel. The static pressure, the sum of the plasma pressure and the magnetic pressure, develops a gradient so that the static pressure increases as Io is approached at the expense of a decrease in the dynamic pressure of the torus flow. Had the flow been supersonic then the static pressure should be too low to be able to overcome the dynamic pressure. In this case to achieve deflection a shock front would form in front of the obstacle. This situation is unlikely to occur at Io because the magnetic field is very strong, approximately 2000 NT, and for typical torus densities the flow is sub-Alfvénic. However, it would occur for high torus densities and appears to have occurred marginally in front of Europa, as discussed later.

The flow is clearly deflected by Io. When Galileo passed in front of Io the magnetic field was elevated above ambient levels (e.g. Russell et al. 2000). When Galileo passed behind Io on pass 80, the flow was observed to bend as if it were closing into a void behind the obstacle.
are creating the large ion cyclotron waves seen around Io. Kinetic processes lead to the inferred fast neutrals that help populate the torus. Kinetic processes both drain flux tubes of energetic particles and supply flux tubes with cold particles as they are dragged across the polar region of Io. At the same time hydrodynamic forces slow down the flow, deflect it and reaccelerate it. It is probable at Io that MHD codes, even with empirically derived mass-loading rates, cannot ade-
quately describe the processes and that we need a hybrid code addressing the kinetic processes and the global interaction. Such a code has not yet been applied to Io.

2.2. The mass-loading process

The torus plasma corotates with Jupiter coupled to the ionosphere by field-aligned currents as described above. At the orbit of Io the corotational velocity is 4 km/s. Since Io orbits at 17 km/s, the plasma is streaming past Io at 57 km/s as illustrated in Fig. 7. When ions in Io’s exosphere become ionized in this flow they experience the electric field associated with the relative flow of plasma and the exospheric particles, nominally 57 km/s, but possibly greater in some regions and less in other regions. Newly created ions form a ring beam in the frame of the plasma flow and execute a cycloidal path in Io’s frame as shown in Fig. 7. The ring beam is unstable to the generation of ion cyclotron waves that over time restore the ions to a more thermal distribution. An example spectrum of these waves is shown in Fig. 8.

The existence of ion cyclotron waves at the SO2 and SO3 gyrofrequencies (Kivelson et al., 1996; Russell and Kivelson, 2000) was not so much a surprise in the Galileo data as were their amplitudes and spatial extent. Ions were being born far from Io. To be transported to such an extent, up to about 20 Io radii outward from Io, requires that particles to travel as fast neutrals. They must be fast or they would dissociate from the observed SO2 and SO molecules to sulfur and oxygen atoms, and they must be neutral to cross the magnetic field lines. A similar fast transport of neutral sodium had been seen and attributed to the acceleration of Na+ followed by charge exchange neutralization before the ion had left Io’s atmosphere (Wilson and Schneider, 1999). A similar mechanism appeared to be working for SO and SO2 as well (Wang et al., 2001) as illustrated in Fig. 7. If the mechanism were to work at the full 57 km/s the resulting ions in the outer torus would be hotter than observed. Thus it appears that the fast neutrals are formed in a region of slowed flow. This is consistent with the coolness and extent of the inner torus as well (Cowen et al., 2003). Neutrals that are launched inward produce cooler ions when picked up than neutrals that are launched outward. Moreover, the slower are the fast

Io (Kivelson et al., 1996). Directly behind Io the flow velocity was small and the ion temperature cold as if the plasma had been picked up in a very slow flow. These flow directions are shown in Fig. 6. Clearly, there is very little flow crossing Io itself and the electrical potential drop across Io is very small. Nevertheless, the plasma loading process does very much slow the flow at Io, causing a large region of best field lines in which field-aligned currents are flowing. These field-aligned currents couple the equatorial magnetosphere and torus to the jovian ionosphere. In the jovian ionosphere the closure current flows through the resistive ionosphere and the resulting $J \times B$ force acts to decelerate the ionospheric plasma. In the magnetosphere the closure current flows on pressure gradients and in curved portions of the magnetic field to accelerate the magnetospheric plasma up to corotational velocity. As we discuss next the continual addition of mass by Io to the magnetospheric ion content causes the plasma to drift outwards stretching the magnetic field and carrying it outward. Conservation of angular momentum slows the angular velocity of the flow when this occurs so that the ionosphere must continue to transfer momentum to the magnetosphere from the orbit of Io almost out to the magnetopause.

Io is an excellent example of the interplay of kinetic and hydrodynamic processes. Kinetic processes

![Fig. 6. Galileo observations showing the bending of the flow into the void behind Io on the B pass. Dashed lines show possible streamlines consistent with the flow. The types of waves seen along the trajectory are also shown.](image-url)
neutrals, the lesser extent they penetrate into the inner magnetosphere. Thus it appears that the fast neutral plasma source mechanism can directly explain features of the inner (cold) and outer (warm) torus.

3. Centrifugally driven circulation
The amount of plasma added to the magnetosphere by Io is great. Thus in addition to the kinetic effects such
as wave generation there are dynamic effects on the plasma torus. The centrifugal force of the torus ions is sufficient to drive outward motion of the plasma (Vasyliunas, 1983; Russell, 2001). This is enabled both because Jupiter is a rapid rotation and because Io provides its mass well outside synchronous orbit. Table 1 shows the factors that affect centrifugal force at the magnetized planets. If mass is added to a magnetosphere outside the distance at which a satellite orbits the planet at the same rate that the planet rotates, then the outward centrifugal force of any material, up to equatorial speed, is greater than the inward force of gravity and the centrifugal force stretches the magnetic field on which the ions gyrate. At Earth this distance is 6.6 R_E at Jupiter only 2.3 R_J and at Saturn even smaller, 1.8 R_S. At Earth the ionosphere supplies mass to the outer magnetosphere but this mass-loading rate is small and the magnetosphere does not extend much past synchronous orbit. At Jupiter there is a large supplier of mass, Io, at 5.9 R_J far beyond synchronous orbit and there is a long way from Io to the Jovian magnetopause. At Saturn the rings and icy satellites all contribute to the magnetospheric mass budget and set outward force on the field lines but it is thought this mass-loading is much less than at Jupiter.

Baguhl (1994) used the Voyager plasma density data to deduce isodensity contours for the Io torus. These are shown in Fig. 10. If we integrate these vertically and azimuthally we obtain the masses per Jovian radius shown on the top of the figure. If we then assume that these numbers represent a steady state of the torus being supplied by Io at 5.9 R_J at a rate of one ton per second we obtain the radial velocity needed to remove the ions to maintain steady state. We see that the inner torus must move outward fairly slowly at about 9 m/s but the outer torus moves much more quickly about 68 m/s. Nevertheless, it still takes over a week to move 1 R_J at this rate (and several months in the immediate vicinity of Io).

The mass-loading at Io has far reaching effects. First, it stretches the magnetic field into a magnetodisk configuration as sketched in Fig. 11. This pushes the magnetopause out further into the solar wind than had the magnetosphere been empty. Second, it powers a circulation of the plasma in the magnetosphere. This circulation moves radially even more quickly as the plasma rotates with Jupiter. This circulation is needed to rid the magnetosphere of the ions added at Io.

The circulation pattern was first proposed by Vasyliunas (1983) and is sketched in Fig. 12. The stretching of the flux tubes that swing out into the tail leads to reconcentration and the formation of islands of ionized plasma that are shed down the magnetojet. Flux tubes that are emptied of plasma return to the inner portion of the magnetosphere only to become mass-loaded by Io once again. There is now much evidence for this circulation pattern. Numerous pieces of data including a radially connected Europa wake, magnetic flux conservation, and stress balance have quantified the radial velocity profile (Russell, 2001). Observation of the dipolarization of the tail field has given support for

![Fig. 10. Voyager 1 density estmimates for Io torus. Isodensity contours have been integrated to give integral shell densities and the required outward flow velocity to maintain steady state (adapted from Baguhl 1994).](image)

**Table 1**

Factors affecting centrifugally driven circulation

<table>
<thead>
<tr>
<th>Planet</th>
<th>R_p (km)</th>
<th>v (m/s)</th>
<th>G (ms⁻¹)</th>
<th>R_mach/R_mach</th>
<th>Plasma source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury</td>
<td>2440</td>
<td>1.24 x 10⁻⁴</td>
<td>3.3</td>
<td>96</td>
<td>None</td>
</tr>
<tr>
<td>Earth</td>
<td>6371</td>
<td>7.29 x 10⁻⁵</td>
<td>9.8</td>
<td>6.6</td>
<td>Ionosphere</td>
</tr>
<tr>
<td>Jupiter</td>
<td>70000</td>
<td>1.77 x 10⁻⁴</td>
<td>25.6</td>
<td>2.3</td>
<td>Io</td>
</tr>
<tr>
<td>Saturn</td>
<td>60000</td>
<td>1.71 x 10⁻⁴</td>
<td>10.8</td>
<td>1.8</td>
<td>Rings, Moons</td>
</tr>
<tr>
<td>Uranus</td>
<td>25500</td>
<td>1.01 x 10⁻⁴</td>
<td>8.6</td>
<td>3.2</td>
<td>Moons</td>
</tr>
<tr>
<td>Neptune</td>
<td>24830</td>
<td>1.01 x 10⁻⁴</td>
<td>10.1</td>
<td>3.4</td>
<td>Moons</td>
</tr>
</tbody>
</table>
the reconnection postulated (Russell et al., 1998) and observations of nearly empty magnetic flux tubes in the Io torus have provided evidence for the return of the emptied flux tubes back to the orbit of Io (Russell et al., 2000).

4. Europa

Outwardly Europa shows none of the violent volcanic activity evidenced by Io and has a much older surface. Nonetheless, Europa shows much evidence of also providing mass to the Jovian magnetosphere, albeit on a scale much reduced over that at Io. Europa is more known for its strong electromagnetic induction signal. The changing magnetic field outside Europa is apparently excluded from the interior of the body by an electrically conducting shell, one clearly close to the surface. Physically the most likely candidate for an electrically conducting shell is salty water. Ice is not sufficiently electrically conducting. In this section we review first the evidence that Europa adds mass to the jovian magnetosphere and how this may affect the torus-moon interaction. Then we examine the evidence for and implications of electromagnetic induction.

4.5. Evidence for mass-loading by Europa

The first evidence for mass-loading by Europa was provided by Pioneer 11. Intriligator and Miller (1982) showed periodic plasma enhancements that they interpreted as a plume arising at Europa and spiraling outwards. This idea was an advance over conventional wisdom in several respects. It identified Europa as a source of mass for the magnetospheric plasma and it hypothesized a steady outflow in the vicinity of Europa and not stochastic flux tube interchange. Once Galileo began its orbital tour of the jovian system it quickly showed that this plume existed by its magnetic signature shown in Fig. 13 (Russell et al., 1999). Galileo clearly saw a repeated wake-like signature on successive planetary rotations. However, this phenomenon does not repeat on every orbit of Galileo indicating that the European plume is a transient feature. Its appearance could depend either on transient events in the tenuous European atmosphere or temporal variations in the density of the corotating magnetospheric plasma. Close to Europa ion cyclotron waves have been reported by Volwerk et al. (2001). These also suggest

Fig. 11. Magnetic field lines in Jupiters noon-midnight meridian showing the stretched field and the current sheet in the magnetodisk region (Russell, 2001).

Fig. 12. Circulation of plasma in the Jovian magnetosphere as proposed by Vasyliunas (1983) (left). Magnetic meridian views of the magnetic field in the tail being stretched until it reconnects forming an island of plasma that is eventually sucked down the tail and lost from the system (right).
that Europa behaves similarly to Io in its supply of mass to the Jovian magnetosphere but at a much reduced level.

The final piece of evidence for an Io-like mass pickup interaction at Europa is the behavior of the magnetic field as Galileo passed Europa on orbit E12, as illustrated in Fig. 14, when Galileo passed within 205 km of the surface. Here the magnetic field profile repeatedly steepened into a shock-like profile and then relaxed as if the Mach number of the flow was close to unity and the flow properties were varying taking the interaction into and out of the supersonic regime. Clearly, the plasma interaction is having a zeroth order effect on the flow past Europa. The maximum magnetic field strength increase due to electromagnetic induction in a vacuum (see next section) is 50%. The more than doubling of the field here is governed by the pressure needed to deflect the incoming flow. The combined evidence from the Europa, plume and the waves in Europa’s wake is that mass addition is sufficient to affect the flow and magnetic field at Europa. However, the solar wind interaction with Venus illustrates that electromagnetic induction in which currents are induced by a time varying field is capable of deflecting a flowing magnetized plasma as we have here so we cannot rule out other interaction playing a role without further detailed study.

4.2. Electromagnetic induction

When a magnetic field is switched on in the region around a highly electrically conducting sphere the magnetic field lines initially do not penetrate the conductor as sketched in Fig. 15. The exclusion occurs because currents flow in the conductor producing the additional magnetic field that leads to the exclusion and the magnetic field pattern shown. This phenomenon is often referred to as Lenz’ law. In the case of a uniform field surrounding a sphere the currents produce a dipole field whose polar values cancel the uniform field at two points and increase it by 50% around a ring. If the sphere is infinitely conducting, the currents flow forever and the field never penetrates the sphere. If the sphere has finite conductivity the currents eventually decay and the field lines penetrate the sphere. Jupiter’s tilted dipole with assistance from its magnetospheric ring current produces a variation in the magnetic field external to Europa that is very similar to the situation sketched in Fig. 15 with the exception that there is a nearly constant vertical magnetic field in addition to the variable radial magnetic field. When Europa is encountered at different magnetic latitudes, it should distort the magnetic field to varying extents. The magnetic field of the Jovian magnetosphere at Europa as the planet rotates is given in the inset in Fig. 16. The
Fig. 14. Evidence for the shock-like interaction of the coronating magnetospheric plasma with Europa. Magnetic field magnitude along a pass of Galileo spacecraft from Europa on pass E12 on December 16, 1997, when Europa was near the center of the torus. The insets show four reformation of a weak shock indicating that the flowing plasma is being deflected by the moon. This is much different than the vacuum approximation used to analyze the Europa induction measurements. Closest approach was at 1203:30 UT at an altitude of 20 km.

Fig. 15. The exclusion of a uniform magnetic field by an infinitely electrically conducting sphere.

The main plot in Fig. 16 is the measured induced moment in the $Y$-direction (radially inward) versus that expected if Europa were a perfect electric conductor with a radius equal to that of the surface of the moon (Kivelson et al., 1997). It is clear that the conductivity of Europa must be high and the radius of that conductor be close to that of
Europa itself. We caution, however, that the analyses in Fig. 16 show only induction effects treating the region exterior to Europa as a vacuum and, as Fig. 14 shows, clearly it is not always a vacuum. There can be large plasma effects. These must be accounted for before we truly understand how conducting is the interior of Europa.

5. Callisto

We temporarily skip Ganymede and move out to Callisto that was not expected to have a global ocean of water. Callisto exhibits less evidence for an atmosphere that interacts with the corotating plasma and would be expected to have a simpler moon-magnetosphere interaction. Counter to expectations for a body that is expected to be frozen there is evidence for an induction signature. Fig. 17 shows a series of measured vector magnetic fields in Callisto’s equatorial plane and those predicted from induction (Kururana et al., 1998). In fact the first two flybys of Callisto, C3 and C9, very much resembled the vacuum induction prediction. However, none of the remaining encounters have approached this ideal state. The apparent reason for this failure is that each of the other flybys for which data are available took place closer to the magnetodisk current sheet where there is significant flowing plasma running into Callisto. This produces an unsteady by very Venus-like interaction. Again we must be cautious of plasma effects in the data.

6. Ganymede

The discovery of an intrinsic magnetic field at Ganymede was a complete surprise. The known volcanic activity of Io was consistent with a hot interior and possibly a magnetic dynamo, but the cold icy and rocky Ganymede should not have a liquid metallic core and a dynamo according to the conventional wisdom at the beginning of Galileo’s mission. Nevertheless, as sketched in Fig. 18, Ganymede does indeed produce a magnetosphere within Jupiter’s magnetosphere (Kivelson et al., 1997). Magnetospheric features include a closed magnetic field region, open polar field regions and a magnetopause. However, unlike the Earth’s magnetosphere (and unlike Europa discussed above) there is no distinct upstream sheath and certainly no shock. The initial model for this magnetosphere was simply a dipole field (of Ganymede) superposed on the Jovian background field. A more sophisticated model employing magnetopause and tail currents and a multi-pole internal field has been developed by Stone and Armstrong (2001). This model improves the fit to the

Fig. 17. Time series of magnetic field vectors compared with predicted vacuum induction (Kururana et al., 1999).

Fig. 18. The connection of Ganymede’s intrinsic magnetic field with Jupiter’s.
individual passes but as of this date has not been tested against particle absorption features.

7. Summary and conclusions

The four Galilean satellites are quite varied in their properties and consequently quite varied in their styles of interaction with the jovian plasma environment. Io adds approximately a ton of sulfurus material to the magnetosphere every second. This material is ionized, and accelerated to corotational velocities. This material provides the driving force that powers the circulation of plasma in the magnetosphere. The associated centrifugal force distends the magnetic field lines into a magnetodisk. The circulation pattern includes radial flow that allows the Io torus material to be carried far out into the magnetosphere where reconnection can separate the ions from the magnetic field allowing empty flux tubes to return to the inner magnetosphere and to repeat the filling/emptying cycle.

Europa represents a transition from the strongly mass-loading Io to the moons Ganymede and Callisto that have much more tenuous atmospheres. These are signs of mass-loading at Europa but on a much smaller scale than at Io. Europa does have a strong inductive magnetic field consistent with an electrically conducting interior with a radius equal to nearly the entire radius of the moon. Callisto surprisingly also has such an inductive signature. Finally, Ganymede has its own intrinsic magnetic field and forms a small magnetosphere inside Jupiter's vast magnetosphere.

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Further reading