The Galilean Moons and the Nature of their Magnetic Fields

A Thesis Submitted in Partial Satisfaction
of the Requirements for the Degree of
Bachelor of Science in Physics
at the
University of California, Santa Cruz

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June 1, 2009

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ABSTRACT

The Galileo spacecraft’s magnetometer data allowed for an understanding of the Galilean satellites’ internal magnetic fields. My objective was to learn the nature of these fields and see if they are consistent with geological and observational data by reviewing all relevant papers and seeking parallels or inconsistencies between them. The results show that Europa and Callisto have internal brine oceans responsible for their oscillating fields, Ganymede either generates its own field through a weak dynamo process, or possesses significant remnant magnetization from a strong dynamo in the past, and Io has no appreciable internal magnetic field.

INTRODUCTION

The Galilean Satellites, also known as Jupiter’s four largest moons, Io, Europa, Ganymede, and Callisto, were discovered by Galileo Galilei between January 7 and March 2, 1610. Galileo would later reveal to the Ptolemaic world that not all objects revolve around the Earth, and that these Galilean satellites instead orbit Jupiter, promoting the Copernican theory of a heliocentric universe. This was the first solid evidence proving that the Earth was not the center of the universe. The moons themselves were named by Simon Marius, who claimed to have independently discovered them along with Galileo, and would ironically be identified as lovers or captors of Zeus.

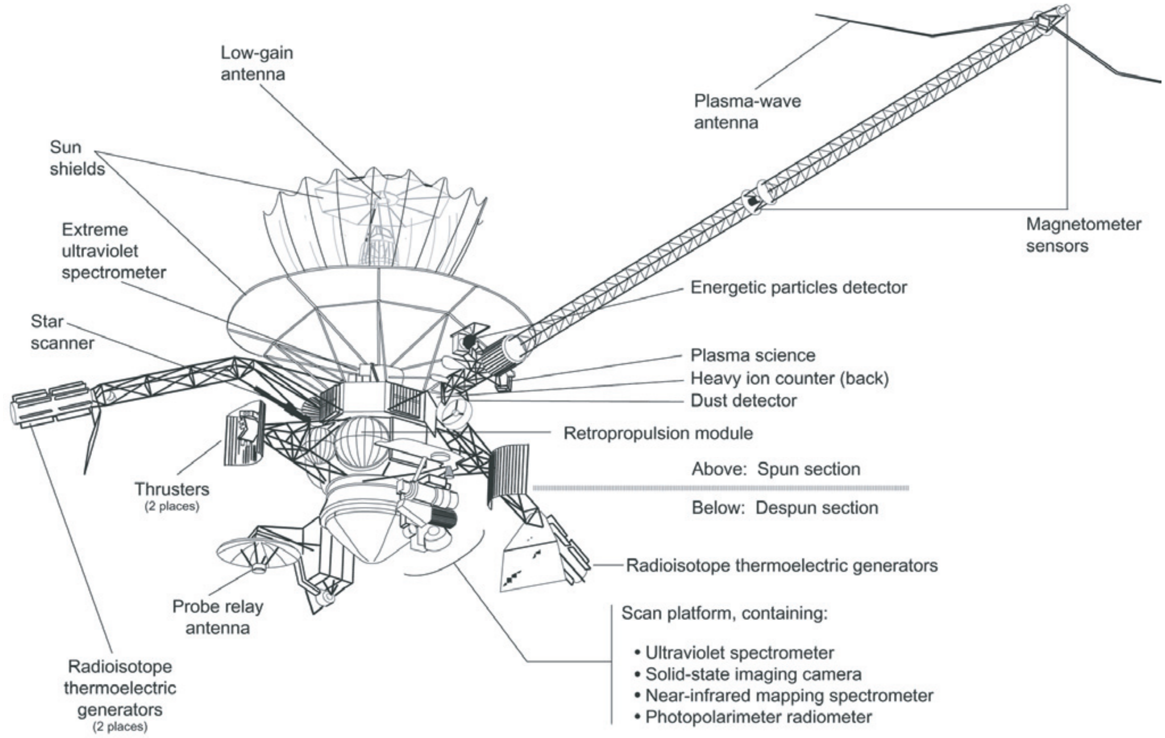
Parameter	Io	Europa	Ganymede	Callisto
Mass (kg) (×1023)	0.8932	0.480	1.482	1.076
Density (g/cm^{-3})	3.518-3.549	3.014	1.936	1.839
Mean Radius (km)	1818.1 ± 0.1	1560.7 ± 0.7	2634.1 ± 0.3	2408.4 ± 0.3
Jovian Ambient Field (nT)	1835	420	120	35
Orbital radius in Jupiter Radii (R_J)	5.9	9.4	15.0	26.3

Table . Physical characteristics of the Galilean Moons.[1]

The timing of the orbits of these special moons would significantly help in the development of longitudinal measurements, and would eventually be used by Ole Christensen Rømer in experiments to calculate a rough estimate for the speed of light in the 1670's. Io, Europa, and Ganymede, the innermost moons, orbit in a 4:2:1 Laplacian resonance, a remarkable phenomenon not yet fully understood. Even the orbits of Ganymede and Callisto display a 7:3 resonance, the least probable of all known resonant orbits.[2]

Early spacecraft would provide geological detail of the moons, but data on their magnetic fields was not a priority. Magnetometer data from Pioneer 10 and 11, as well as Voyagers 1 and 2, focused mainly on the Jovian magnetosphere, since close flybys of the Galilean moons were not possible. The imaging of the Galilean moons only sparked further curiosity as to their origins and details. The idea that Jupiter formed through a process of concurrent accretion of gasses and solids provided rough estimates for the relative composition of the moons.[3] The formation of the Galilean satellites through a "gas-starved" accretion model,[4] provide a reasonable explanation for the observed composition of ices, rock, and metals within the moons and the ratios between them. This formation method involves slow accretion of gas onto Jupiter, and long mass accretion times for the satellites, allowing for sufficiently low temperatures for ice and hydrated silicate stability within the moons.[4] Yet, the data obtained from the quick flybys of Pioneer and Voyager missions had limitations in constructing an overall picture of the Jovian system, requiring a more focused mission.

Shortly after the launches of Voyagers 1 and 2 in 1977, funding was approved for the Galileo spacecraft, which would carry the latest designs in remote sensing instruments. Due to developmental problems with the US shuttle program and the Challenger Space Shuttle disaster, it was not until October of 1989 when Galileo was finally sent to gather detailed magnetic data from Jupiter and its Galilean satellites.[5] On December 7, 1995, Galileo began orbiting Jupiter and would gather valuable data for nearly eight years. Amongst the assortment of instrumentation on the Galileo spacecraft were two magnetometer sensors attached to an 11 meter, fiberglass boom in order to avoid interference from the spacecraft itself (Figure). These magnetometers would provide detailed information about the nature of the magnetic fields of all the Galilean satellites as well as Jupiter.



Galileo spacecraft

Figure 1. Diagram of the Galileo spacecraft including labeled instrumentation.

Initial magnetometer data revealed significant detail of not only the magnetic fields of the Galilean moons, but also the inner structure of both Europa and Callisto, providing perhaps the best evidence for entire spherical layers of liquid salty water. Galileo detected almost purely induced magnetic fields of magnitudes that require a near-surface electrically conducting layer on each of these moons. Furthermore, the data showed that Ganymede creates, or had created its own magnetic field through a dynamo mechanism, the same method of magnetic field generation that produces the magnetic field of Earth. Yet, the most inconclusive data came from Io, where neither a dynamo, nor a purely induced field could explain its nature.

THE INDUCED FIELDS OF EUROPA AND CALLISTO

Jupiter's magnetic field axis is not as simple to define as the Earth's due to the complexities within Jupiter and how its magnetic field is generated. It is approximated as a centered, tilted dipole, although it does not correspond with Jupiter's center of mass. On the basis of Pioneer 10 and 11 measurements, its magnetic axis has been calculated to be offset from its rotational axis by about 10 degrees. As Jupiter rotates about once every 10 hours, its magnetosphere wobbles due to its inclination, resulting in time variations in magnitude along Jupiter's ecliptic (Figure 2). The Galilean satellites experience this varying field, and in accordance to Maxwell's equations, magnetic fields may be induced on the moons. However, the important requirement necessary for this to occur is that a significant layer of electrically conducting material must be present in the moons.

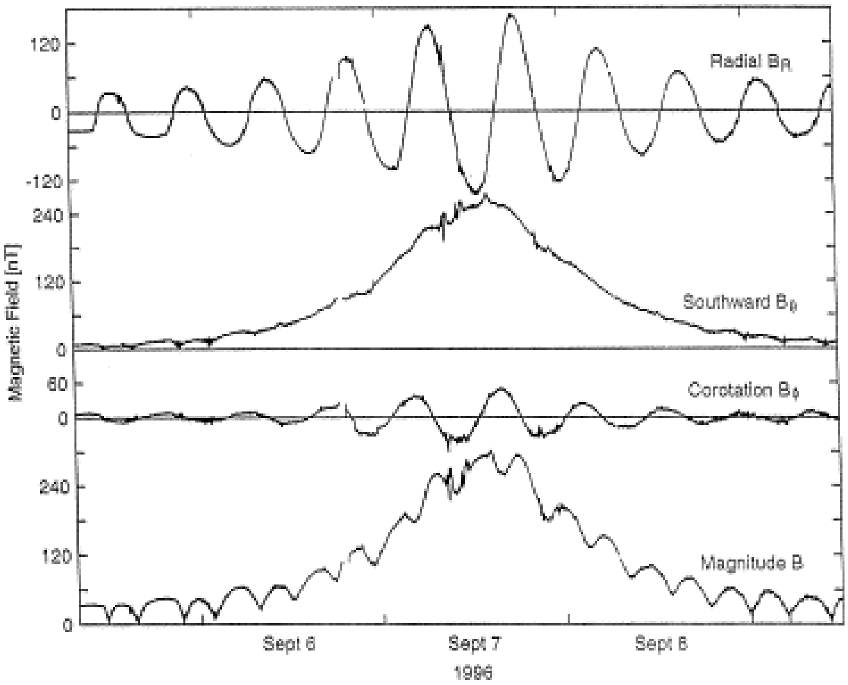


Figure 2. Galileo's magnetic field measurements from 28 R_J on Sept. 5, to 26 R_J on Sept. 9. The spacecraft passed through closest approach of 10.7 R_J on Sept. 7, corresponding to the peak in the southward measurement. Fluctuation is most apparent in the radial component, B_R.[6]

Europa

Europa orbits at a radius of 9.4 Jupiter Radii (R_J), corresponding to an ambient field with a radial component that oscillates with an amplitude of ~230 nT,[7][8] and an azimuthal component that oscillates with an amplitude of 60-75 nT.[8] The mean field strength of the Jovian field at this orbital radius is 420 nT.[1] Much like sticking a magnet through a copper coil, electric current is induced. Conceptually this is just Faraday's Law, $\times E=-\partial B\partial t$, except the copper coil is a conducting layer within Europa. Keeping in mind the Biot-Savart Law which states, "Steady currents give rise to constant magnetic fields," and Ampere's Law, $\times B=\mu 0J$, it is apparent that the induced current from the time varying Jovian magnetic field, induces a magnetic field of its own on Europa. The question of what this conducting material is, or where it must be located within the moon, has to do with the magnitude of the induced magnetic field.

The Galileo spacecraft made a series of flybys on Europa that were geared towards placing a value on the induced magnetic field. As the spacecraft approached Europa on each of these passes, measurements of the enhanced Jovian background field led to the determination of Europa’s magnetic field (Table 2).

Jovian Ambient Field	Induced Field at Magnetic equator	Induced Field at Magnetic poles
420	120	240

Table . Galileo measurements for Europa (nT). The dipole model was found by fitting a Europa-centered dipole to the difference between the background field and the measurements.

Europa formation models in principle allow for a metallic iron-nickel core within Europa, effectively acting as a perfect conductor. However, it would have to extend to about 320 km from the surface to describe the magnitude of the induced field. This corresponds to a core mass of 6.4×1022 kg, grossly inconsistent with the constraints from gravitational measurements (Europa’s mass is only 4.8×1022kg). It turns out that the contribution from Europa’s actual core is negligible, and the magnitude of its induced field is most likely due to a shell of water with a relative amount of dissolved salt.

There has been strong geological evidence for a layer of water within Europa. The general lack of impact craters suggests that the moon is able to resurface itself. The moon’s overall density of $3.014\mathrm{gcm3}$, suggests that it is primarily composed of silicate rock. Yet, IR and albedo measurements show that the surface is dominated by salt water ice, and allow for a fairly thick (several to ~100 km) layer.[1] Tidal heating, due to the gravitational interaction between the orbiting Galilean moons and Jupiter, may result in melting an entire layer of this water ice near the surface.[9] Observed fractures on

Europa’s surface would expose water, but due to the buoyancy of ice, only water that has boiled over and produced frost can rise to the surface. This would explain the resurfacing of Europa, and require a liquid water layer beneath the icy surface.[10] The resulting argument for a spherical shell of liquid salty water is not only consistent, but also dependent on the observed induced magnetic field.

Callisto

Much like Europa, Callisto’s magnetic field is entirely induced. There is no evidence for a metallic core, so the observed field can only be explained by an induction process. The moon orbits at a radius of about 26.3 R_J and experiences an ambient field whose radial component oscillates with an amplitude of ~40 nT,[7][8] and an azimuthal component that oscillates with an amplitude of 8 nT.[8] The field strength of the Jovian ambient field is 35 nT at this orbital radius. Although Galileo flybys experienced some trouble determining values for Callisto’s magnetic field due to possible current flowing in the ambient plasma, a couple of flybys agreed almost perfectly with an induced dipole model. These flybys (C3 and C9), occurred when the Jovian ambient field was oriented in opposite directions, and show the induced dipole moment of Callisto with opposite orientation as well.[8] Much like Europa, measurements of the enhanced Jovian background field led to the determination of Callisto’s magnetic field (Table 3).

Jovian Ambient Field B_o	Induced Field at magnetic equator	Induced Field at Magnetic poles
35	~14	< 30

Table . Galileo measurements for Callisto (nT).

The fitted magnetic field is well below the ambient field, which is the natural upper limit, and is best explained by a near surface layer of conducting fluid. Gravitational constraints measured by the same Galileo passes, show that Callisto’s interior is composed of a mixture of rock and ice, and allow for a surface shell of ice that is no more than 350 km thick.[11] It is natural to conclude that a liquid salt water shell is the conducting layer responsible for Callisto's induced magnetic field. However, the same heating process thought to provide Europa with its liquid layer, may not explain Callisto's similar conducting layer. Callisto is heavily cratered and appears not to possess any capability of resurfacing its exterior, it does not have the same tectonic landforms that suggest surface motion over a liquid interior, and it orbits outside the realm where tidal heating takes effect. So, the only solid evidence of a salty water layer within Callisto is the detected magnetic field itself, which is best explained by an internal ocean 10 km thick.[1] Using stress independent, Newtonian viscosity models, an ocean within Callisto would be unstable against convection and freeze in about 10^8 years.[12] The existence of ammonia in the internal ocean would act as an antifreeze and is perhaps the only way for Callisto to maintain its liquid layer. It has long been suggested that trace quantities of ammonia, perhaps up to 5 wt% in Callisto and Ganymede, may lower the freezing temperature of their subsurface oceans by up to 100 K (Figure 3).[1][13] If this is the case, then it would perfectly explain everything in regards to Callisto's magnetic field. However, a more physically reasonable water-ice model, that involves stress dependence and non-Newtonian viscosities, suggests that a subsurface ocean could maintain its liquid state without the requirement of ammonia.[12] Since these two arguments are completely compatible, most likely Callisto exhibits a combination of both.

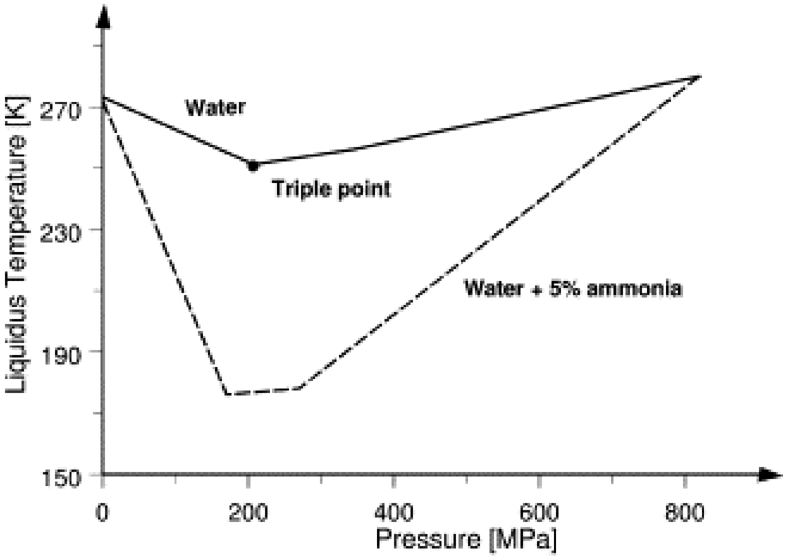


Figure 3. Simplified phase diagram of water ice and of water ice + 5 wt% ammonia. [12] The Liquidus temperature is the temperature above which the solution is completely fluid and, no solid phases occur.

GANYMEDE'S INTRINSIC FIELD

Ganymede is the largest satellite in the solar system, with a diameter greater than Mercury and Pluto. A total of five close passes were made by the Galileo spacecraft detailing a magnetic field well above the Jovian ambient field of 120 nT, which corresponds to Ganymede's orbit of 15.0 R_J. In addition, a portion of Ganymede's magnetic field (~100 nT at the induced poles) was seen to vary in time, suggesting an induction process much like Europa and Callisto.[14] This is consistent with implications that Ganymede may have an internal ocean as well.[15] The detected equatorial field strength at the fitted dipole was found to be about 720 nT,[14] and the field at the poles was measured to be 1200 nT[1] (Table 4).

Ambient Field (nT)	Equatorial Field (nT)	Field at Poles (nT)
120	720	1200

Table . Galileo measurements for Ganymede.

The fact that the field strength measured for Ganymede is far higher than the ambient field requires a different explanation than a solely induced field.

There are number of gravitational constraints on the internal structure of Ganymede, but perhaps the most important is a very small value for its axial moment of inertia, $C/MR^2 = 0.3105 \pm 0.0028$[16] ($C/MR^2 = 0.4$ for constant density). For a rocky body, this is among the smallest in the solar system, indicating a highly differentiated interior with a large concentration of mass towards its center. Using infrared reflectance spectra, hydrated salt minerals were detected on the surface of Ganymede.[15] As with Europa, where these minerals exist as well and were thought to have leaked to the surface from a subsurface ocean, Ganymede most likely possesses a significant subsurface ocean 10 km thick made up of salty water rich in $MgSO_4$, as indicated by spectral analysis.[15] This would account for the detected induced field with explanations similar to that of Europa.

The detected magnitude of Ganymede’s magnetic field can be described by remnant magnetization, magneto-convection, or dynamo action. However, the best explanation is confined by the internal structure and thermal state of the moon.[17] The requirements for remnant magnetization and magneto-convection in salt water are not reasonable on Ganymede. In order for remnant magnetization to work, a sufficiently large concentration of magnetite and an external magnetizing field larger than the ambient field must exist in a rock shell within Ganymede.[17] Magneto-convection in Ganymede’s conducting liquid layer is not self sustaining and in order to produce a field of detected magnitude, must be several hundred kilometers thick.[17] These are both outside the bounds of reasonable parameters for Ganymede. So, if remnant magnetization and magneto-convection in

Ganymede’s conducting liquid layer are ruled out, then only magneto-convection in a liquid metallic core, or dynamo action may explain the intrinsic field.

Ganymede’s highly differentiated internal structure suggests a dense core of pure iron, or an alloy of iron and iron sulfide (FeS) of radius 400-1300 km thick.[16] For the core to be at least partially molten, an FeS-silicate rock boundary must be at a temperature upwards of about 1300 K, whereas a pure iron core would necessitate temperatures nearing 2000 K.[17] Dynamo action requires a rotating body, with at least a partially fluid conductor in order to generate enormous electrical current. This is essentially a self generating form of the thermoelectric effect, where temperature differences are ultimately provided by the Coriolis force due to Ganymede’s rotation, and convection within the liquid or partial liquid metallic core. The generated electrical current then induces a magnetic field, which conceptually is just Ampere’s Law again ($\mu 0J=$

$\times B$). In reality, a mathematical description of dynamo action requires equations of Magnetohydrodynamics (MHD) which include the induction equation;

$\partial B\partial t=$

$\times v\times B+\nu m$

$2B$ (where $\nu m=1\mu 0\sigma$),[18] which is non-dimensionalized by taking the ratio of the convective and diffusive terms. This is known as the Magnetic Reynolds Number ($Rm=$

$\times v\times B\nu m$

$2B$), an important factor in determining whether magnetic fields are tied to fluid motions.

Ideal equations for MHD consist of an array of equations describing everything from thermal evolution to magnetic and gas pressure to fluid motion. Since the complexities of describing dynamo action mathematically are so great, the preferred method has become the reproduction of planetary and solar dynamos through the use of numerical models.

Arguments against a dynamo model on Ganymede mainly focus on the maintenance of a core temperature high enough to at least sustain a liquid FeS outer core (~1300 K). Tidal heating alone is not sufficient,[1] and the understanding of remnant heat from the formation of the Jovian system is all but conclusive. In fact, tidal heating is the only significant restoring supplier of heat that Ganymede has to offer, and it is possible that Ganymede's core may have cooled to the point where there is no longer a fluid conductor to produce dynamo action. If this is the case, then remnant magnetization must explain the observed magnetic field, and Ganymede must have produced an unlikely dynamo-driven magnetic field with a surface magnitude on the order of 10,000 nT in the past.[1] This is comparable to the magnetic field strength of Earth.

THE ENIGMATIC MAGNETIC FIELD OF IO

Io is home to perhaps the oddest magnetic field in the solar system. Io's surface is heavily cratered, not by meteor impacts, but through high-temperature volcanism; most likely resulting from erupting ultramafic rock (>18% MgO).[5] Fueled by intense tidal heating, volcanoes on Io regularly spew ions into space, which form a plasma torus that revolves with Jupiter's magnetic field,[19] and a flux tube that electrically couples Io to Jupiter's magnetic poles resulting in an auroral footprint near Jupiter's poles.[20] Tidal heating was also thought to keep Io's large Fe-FeS core at least partially molten, so it was a perfect candidate for dynamo action.[21] However, Galileo flybys on Io's poles showed no evidence for an intrinsic magnetic field. This result was consistent with numerical predictions of a conductively cooling, molten core with no convection due to the tidal heating rate dominating the energy balance of Io’s mantle, resulting in a lack of removed heat from the core.[22] Convection in a liquid conducting core is absolutely necessary for a dynamo process to take place. Previous Galileo data proved to be inconclusive in describing the nature of Io’s magnetic field because of large perturbations from surface waves on the Jovian current sheet, which contains most of the plasma in Jupiter’s magnetosphere.[23]

Initial reports from the Galileo spacecraft showed a field decrease of nearly 40% of the ambient field at closest approach, suggesting either an abnormal amount of iron for an induced field, or an intrinsic dynamo.[24] Since there is no water on Io, only iron has the conductivity necessary to explain an induced field of nearly the same strength as the ambient field. Dipole models suggested a magnetic field on Io with a polar strength of ~2600 nT,[24] far greater than the ambient field strength of 1800 nT. So, even if Io was a perfect conductor, an induction process could only fulfill part of the explanation at best. At this point, a dynamo process had not been ruled out, but was competing with an explanation that did not require any sort of intrinsic field. This explanation was that the Io plasma torus, essentially revolving with Jupiter’s rotation, was generating plasma currents through its interaction with Io.[25] Also, during an early flyby (I0), the Galileo spacecraft unexpectedly passed through Io’s ionosphere, a cool, dense plasma at rest with respect to Io, which added to the effective decrease in the ambient field.[26] The evidence supporting an internally generated magnetic field was deeply flawed in one key assumption. Io was assumed to have a relatively thin ionosphere. This, coupled with near minimum measurements for the plasma torus mass density, would account for only a small percentage of the magnetic field decrease. The fact that Io is home to a thick ionosphere, and interacts with the plasma torus of mean mass density two times greater than previously utilized, threw out the necessity of an intrinsic field.[26]

Galileo's subsequent passes focused on determining whether or not Io possessed an intrinsic field. In fact, passes I24, I25 and I27 in late 1999 and early 2000 (data during the I26 encounter were lost) would prove inconclusive due to the highly dynamic nature of the space surrounding Io.[27] However, the passes were able to provide enough data for an MHD simulation of the interaction between Io and its plasma torus, in hopes to find out whether an internal magnetic moment was required for an explanation. The data revealed that if an internal field is present within Io, it is either inductive, or significantly tilted relative to the spin axis, excluding a "permeable magnetic response."[27] This could only mean that a dynamo generated magnetic field had been ruled out by the simulation.

The last Galileo passes occurred in late 2001 and early 2002. I31 and I32 were high latitude passes over both the northern and southern poles, and would reveal no appreciable internal magnetic field.[28] These passes also showed significant local changes in magnetic field near some of Io's well known volcanoes.[28] These local perturbations had never been considered to have a substantial effect on Io's overall field. Furthermore, an upper limit to Io's internal field was never established, but it is thought to be very weak (< 25 nT equatorial field).

FUTURE EXPLORATION OF THE GALILEAN MOONS

Since Galileo, there have been two missions approved that focus solely on the Jovian system, Juno and the Europa Jupiter System Mission (EJSM). Juno is projected to launch on August of 2011 with the primary objective to study Jupiter's atmosphere and produce details of Jupiter’s dynamo driven magnetic field with very little focus on the moons. EJSM, however, has a primary objective to ultimately determine the evolution process of gas giant planets and the possible formation of habitable moons. Funding for EJSM has been approved with a launch date set for February of 2020. EJSM will consist of two spacecraft focusing mainly on the inner and outer Jovian system. Detailed specification on these crafts have not yet been determined since abstracts for instrumentation are currently being accepted, but the overall design of the spacecrafts have, for the most part, been finalized. Each will have a long boom to accompany magnetometers that will most likely be far more advanced than the older magnetometers on Galileo. This will result in greater precision in the measurements of magnetic fields as the spacecrafts approach the Galilean satellites. Initial orbits will allow each spacecraft to make passes on Callisto and Io before ultimately settling in final orbits around their focused moons of Europa and Ganymede.

EJSM consists of a Jupiter Europa Orbiter (JEO) and a Jupiter Ganymede Orbiter (JGO) with slightly different designs to accommodate their radiation environments. JEO will only encounter Io four times during its 30 month Jovian system tour, which makes it unlikely to produce an upper limit to Io’s intrinsic magnetic field. However, JEO will encounter Callisto nine times, and eventually settle in orbit around Europa. These events will be accompanied by continuous magnetometer data, which will likely confirm an induction process on both of these moons. JGO will also encounter Callisto several times to complement JEO. Ultimately, JGO will settle in orbit around Ganymede where it will remain until orbit maintenance fuel is exhausted. This should provide ample time to continuously map Ganymede’s magnetic field in detail to conclude whether Ganymede harbors a dynamo driven field. Furthermore, the overall goal of EJSM in detailing specifics on giant planet formation, may provide an answer to whether Ganymede's interior is currently hot enough to allow for dynamo action.

CONCLUSIONS

Although the details of Europa's and Callisto's magnetic fields involve a very complex induction process, it is best to visualize in the form of a simple electrodynamic process. Their time varying fields produced by Jupiter's magnetic field precession are analogous to Faraday's law, where electric current is conducted through near-surface brine oceans. These oceans have been, and continue to be confirmed by geological evidence and surface measurements.

The vast bulk Ganymede's magnetic field can ultimately be attributed to a dynamo process. Whether that dynamo still exists is still open to debate. If it does not exist, then remnant magnetization from a very strong dynamo in the past could explain Ganymede's internal field. However, due to Ganymede's slow rotation and likely partial fluid core, a sustained weaker dynamo is the best description for the moon's internal field. Evidence for Ganymede's metallic core is apparent in its relatively small moment of inertia, suggesting a highly differentiated interior. Furthermore, measurements on the surface of the moon imply a subsurface ocean. Magnetometer data showing time variations in a small portion of Ganymede's overall field support these measurements.

The internal magnetic field of Io has been analyzed extensively and proven to be very nearly non-existent. Flybys I31 and I32, focusing on the magnetic poles as shown by dipole models, do not reveal any intrinsic dynamo or significant magneto-convection process.

	Io	Europa	Ganymede	Callisto
Ambient Field	1835	420	120	35
Equatorial Field	< 25	120	720	14
Polar Field	-	240	1200	< 30

Table 5. A summary of field strengths for the Galilean satellites in units of nT.

ACKNOWLEDGEMENTS

Thanks are due to my technical advisor, J. Fortney, for invaluable guidance and discussion. Also, thanks to M. Kivelson for answering questions concerning Io via e-mail.

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