Magnetoconvection Dynamos and the Magnetic Fields of Io and Ganymede

G. R. Sarson, C. A. Jones, K. Zhang, G. Schubert

Data from the Galileo orbiter suggest that two of Jupiter's moons, Io and Ganymede, have intrinsic magnetic fields. The magnetic field of Jupiter alters the nature of the magnetohydrodynamic processes generating these intrinsic fields. Such an imposed field allows appreciable internal fields to be generated in cases where convection cannot otherwise maintain a dynamo. The dipole moment of the internal field can then become aligned with the background field, as is observed for Io and Ganymede. Io might not have a self-sustained intrinsic field in the absence of the ambient jovian field; Ganymede is almost certainly operating as a dynamo in its own right.

Magnetometer data from the Galileo orbiter indicated that two of Jupiter's moons, Io and Ganymede, have significant magnetic fields of internal origin (*1–3*). The most feasible source for these fields is some form of magnetohydrodynamic (MHD) process occurring in electrically conducting liquid cores, similar to the mechanism thought to be responsible for the magnetic fields of Earth and other terrestrial planets (*4*). Indeed, the recent detection of intrinsic fields is one of the strongest indicators that these satellites have the molten Fe-rich cores necessary for such processes (*4–6*). The MHD processes occurring in Io and Ganymede may differ from those responsible for other known planetary magnetic fields, however, in that they take place within the magnetic field of Jupiter. This ambient field imposes a preferred sense of axial direction on the systems, which are otherwise invariant under reflection in the equator, and may also help to initiate convection through the interaction of Lorentz (magnetic) and Coriolis (rotational) forces, resulting in the possibility of magnetic field generation in bodies incapable of self-excited dynamo action (*4, 7*). The abstracted physical problem therefore contains elements of the magnetoconvection problem—where convection is influenced by, and may rearrange, an imposed magnetic field—as well as elements of the conventional dynamo problem—where the magnetic field is entirely self-excited (*8*).

The ambient magnetic field that the jovian moons experience has contributions from Jupiter's intrinsic field and from the field of a plasma sheet in the jovian magnetosphere (*9*). Although the jovian magnetic field is nonaxisymmetric, it corotates with the planet on a time scale much faster than that of the internal MHD processes, and so the relevant contribution to the ambient field is the jovian field time-averaged over a Jupiter rotation. At the orbits of the moons, this field can be approximated by a constant local field, essentially that produced by a simple axial dipole. The average contribution from the plasma sheet is also uniform, and so the net-averaged ambient field is essentially constant and is aligned in the direction of the rotational axis (*9*). The intrinsic magnetic fields of the two moons have been fitted by dipole models (*1–3*). Both dipoles are approximately axial and have moments opposite in sense to Jupiter's axial dipole.

Io and Ganymede have dipole moments of about equal strength; they lie, however, in ambient fields of different strength (Table 1). At the surface of Io, the internally produced magnetic field is of the same order as the ambient field at this distance from Jupiter. Because an Fe-rich core (of eutectic composition) would account for about one-half the surface radius of Io (*5*), and because the internally generated field must decay at least as r^{-3} with radius r, outside this conducting core (the silicate mantle being, to a first approximation, insulating), the intrinsic field in the core must be several times stronger than the imposed field. As the surface magnetic field of Ganymede is larger than the ambient field at its more distant orbit and the core of Ganymede is thought to be only one-quarter of its surface radius (*6*), the intrinsic field must be several hundred times stronger than the ambient field in the core.

It is possible that both Io and Ganymede generate magnetic fields by "true" dynamo processes, with the ambient field of secondary, or negligible, importance. The presence of the ambient field admits a second possibility, however: that the differing strengths of this imposed field and the differing ratios of imposed field to intrinsic field are significant, and that the two moons operate in quite different MHD regimes. Magnetoconvection processes, dominated by the ambient field, may be important in the case of Io (*4*). For Ganymede, it is difficult to see how magnetoconvection could produce an intrinsic field so much stronger than the local ambient field, and so a genuine dynamo is more likely. The ambient field might still play a role in such a dynamo, however; in particular, it might determine the sense of the generated magnetic field.

Here we report calculations of MHD processes in the presence of an ambient field, to evaluate the possibility that such a field could be significant to the magnetic states of Io and Ganymede. We impose fields of varying strengths and attempt to produce intrinsic fields of varying strengths, across a range of convective regimes. We refer to the models as "magnetoconvection dynamos" to cover the range of MHD activity possible.

We make use of a mean-field dynamo model originally set up to model the geodynamo (*10*). To this model we impose a uniform background field $\mathbf{B}_0 = B_0\mathbf{e}_z$, where $\mathbf{e}_z$ is a unit vector in the axial (z) direction. As a first approximation, we model the moons' cores as bodies of constant conductivity surrounded by electrically insulating mantles. Because little is known of the true states of the cores, our model of Earth's core, incorporating a small solid inner core (of radius one-third of the core radius), is retained for simplicity (*11*). We also retain a buoyancy-driven

Table 1. Estimates of some physical parameters of the two moons. The quantity $\mathbf{e}_z$ is a unit vector in the axial direction. The core densities quoted assume a eutectic Fe-FeS composition. The core radii, also dependent on this assumption, are rather poorly constrained; the values given here are somewhat representative. For both moons, the rotation period is identical to the orbital period. In the absence of reliable estimates, the magnetic diffusivity η of both moons has simply been taken as that of Earth, 1 $m^2 s^{-1}$ (*21*). The magnetic permeability μ is taken to be that of free space, μ_0.

Parameter	Io	Ganymede
Dipole moment (10^{12} T m^3)	8* (*1*)	14† (3)
Intrinsic field (nT) at equator, on surface	1300 (*1*)	750 (3)
Ambient field B_0 (nT)	1800 (*1*)	100 (3)
Radius (km)	1821 (5)	2634 (6)
Core radius (km)	950 (5)	660 (6)
Rotation Ω (10^{-5} s^{-1})	4.11	1.01
Density ρ (kg m^{-3})	5150 (5)	5150 (6)

*Along $-\mathbf{e}_z$. †10° from $-\mathbf{e}_z$.

G. R. Sarson, C. A. Jones, K. Zhang, Department of Mathematics, University of Exeter, Exeter EX4 4QE, UK. G. Schubert, Department of Earth and Space Sciences, Institute of Geophysics and Planetary Physics, University of California, Los Angeles, CA 90095, USA.

source of convection appropriate to an internally heated core. Although Io is strongly heated by varying tidal forces arising from orbital interactions with the other Galilean satellites (*12–14*), so that our buoyancy model is clearly not ideal for this moon [tidal heating of Ganymede is at present negligible (*12*)], this source remains a reasonable starting point for investigations. For numerical convenience, the model also retains viscosity (*15*).

The presence of an imposed magnetic field increases the instability of the systems to MHD disturbances, so that a smaller buoyancy force is required to initiate convective instabilities. To obtain the relatively large field strengths (in relatively weak ambient fields) required from the preceding dimensional arguments, however, we need to look at systems far from this linear onset state, where more complex, finite-amplitude flows and magnetic fields interact nonlinearly. In terms of our numerical model, this unfortunately means we cannot obtain values of the viscosity or thermal diffusivity small enough to accurately model the moons' cores (*16*), complex nonlinear calculations being more computationally demanding at small values of these parameters. Nevertheless, numerical solutions capable of modeling the pertinent features of the observed data can be obtained.

For an ambient field of strength appropriate for Io (Table 1), we find that an intrinsic field of the observed strength can be obtained with a relatively weak imposed buoyancy force (*16*). The total field in this calculation is strengthened from the ambient level along the rotational axis but weakened in the equatorial (ecliptic) plane (Fig. 1). This net field, external to the moon, agrees with observational models (*1*).

The intrinsic field produced, although considerably larger within the core than the ambient field, nevertheless decays if the ambient field is withdrawn, causing the system to revert to a state of nonmagnetic convection. This model is thus dependent on magnetoconvective-type processes, rather than acting as a true self-sustaining dynamo. That such a relatively weak imposed field should help toward the generation of magnetic fields can be understood if we consider the traditional mean-field dynamo problem. Toroidal (zonal) magnetic fields are generated relatively easily from poloidal (meridional) fields by the simple shearing action of fluid in differential rotation (the so-called "ω effect" in dynamo theory). The difficulty in obtaining self-excited dynamo action comes in "completing the loop" and generating a poloidal field from a toroidal field; three-dimensional fluid motions of low symmetry are required for this step (*17*). In the present case, however, the ambient field constitutes an existing poloidal field, and so this difficulty is circumvented (*18*).

The imposed magnetic field also imparts a preferred sense of direction to the system, unlike the general case, where **B** and −**B** may be interchanged (*7*). Thus, the sense of magnetic field shown above is significant; solutions of the opposite sign are unstable and soon revert to the above case. The sense of dipole moment is therefore fixed and is antialigned with the jovian dipole moment (*1–3*).

An internally produced field of the strength required for Ganymede, in its relatively weak ambient field, could not be obtained by such magnetoconvective processes. A stronger buoyancy driving force is required (*16*), and the resultant solution essentially operates by a "pure" dynamo process, with the imposed magnetic field effectively negligible (Fig. 2). The sense of dipole moment for this model is not uniquely determined by the imposed field; the corresponding solution with intrinsic field of opposite sign is also stable. In this case, the antialignment of Ganymede's and Jupiter's dipoles might be coincidental; there is clearly a 50% possibility of a dipole being aligned in either direction. In the initial stages of magnetic field generation, however, when the internally produced field was still weak, it is possible that the ambient "seed" field was sufficient to influence the sense of field preferred. As this solution does not reverse polarity, this sense of dipole might then have been retained, even when the internally produced field grew sufficiently to

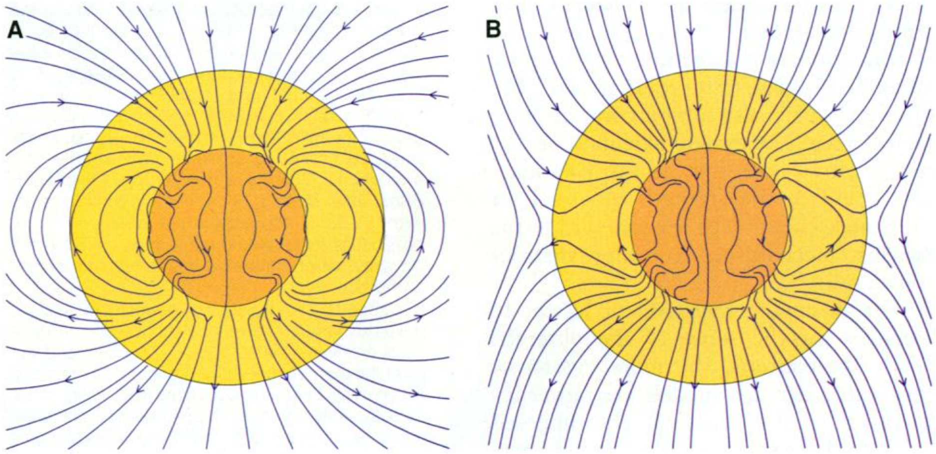

Fig. 1. The axisymmetric meridional field in the model for Io. Using the parameter estimates given in Table 1, we find that the ambient field scales to B_0 = 2000 nT, and the internally generated field at the equator on the surface, to 1300 nT. The interior (orange) region represents the core, and the exterior (yellow) region, the surrounding (insulating) mantle, in which the magnetic field is a purely potential field (as it is in the surrounding space). The core radius is one-half of the surface radius. (**A**) Internally produced field only. (**B**) Total (internal plus ambient) field.

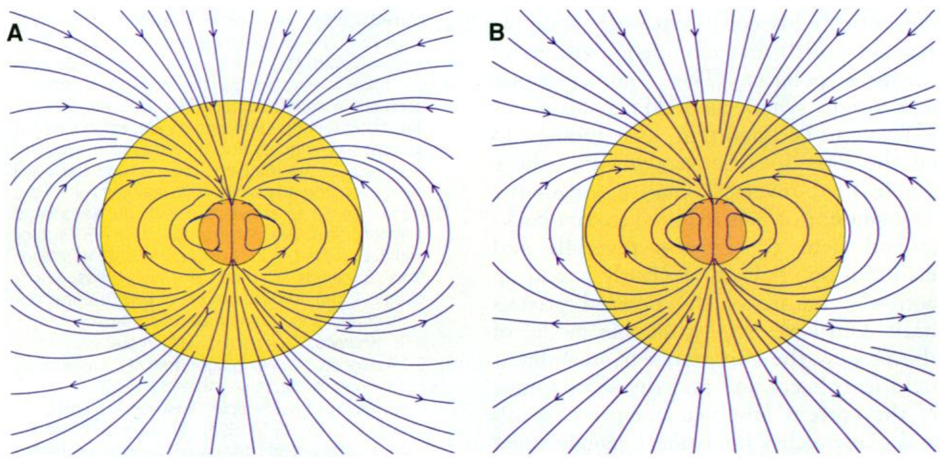

Fig. 2. The axisymmetric meridional field in the model for Ganymede. The ambient field scales to B_0 = 100 nT, and the surface equatorial intrinsic field, to 650 nT. An Fe-rich core (orange) of one-quarter the surface radius is assumed. (**A**) Internally produced field only. (**B**) Total (internal plus ambient) field.

make the imposed field negligible; the antialignment of Ganymede's dipole-moment with Jupiter's could then still be consistently explained with this model.

Io, being physically broadly similar to Ganymede and having a similar dipole moment, could also be modeled by a similar solution. The earlier model, however, has shown that a magnetoconvective state, as suggested by Schubert *et al.* (*4*), remains a viable alternative in the case of Io. If Io is indeed operating by a magnetoconvection-type mechanism, in quite a different MHD regime from Ganymede, this difference must be explained by the different convective states of the two moons. Io is tidally heated (*19*) by orbital interactions with the other Galilean satellites (*12–14*). This tidal interaction heats Io's mantle and inhibits the transfer of heat from the interior, which cannot attain a state of vigorous convection (*20*). In contrast, tidal heating of Ganymede is minimal (*12*), and so a cooler mantle, and a more strongly convecting core, is quite plausible (*4*). The faster rotation rate of Io (Table 1) might also inhibit convection to some degree. The present calculations suggest, in any event, that an intrinsic magnetic field of the strength observed for Ganymede can only be generated by a true dynamo mechanism, requiring vigorous convection.

The magnetoconvective model for Io accounts for the sense of the observed dipole. In contrast, the more vigorously convecting dynamo models are rather insensitive to the sense of the imposed fields, and we must resort to rather speculative arguments to maintain that the antialignment of their intrinsic dipoles with the background jovian dipole is significant. To some extent, this difficulty may be due to limitations in our model. We have, for example, restricted our model to only the equatorially antisymmetric magnetic fields consistent with a dipole symmetry (*10*) and obtained solutions of constant polarity. The complementary equatorially symmetric field may ultimately prove to be important, as is thought to be the case for the geodynamo, whose dipole field reverses polarity irregularly. The amount of bias required from a background field to suppress reversals and maintain one polarity is clearly bound up with the nature of the reversal process itself. Until we have a reliable model of this process, the importance of an ambient field in this context and the significance of the current observed polarities of Io's and Ganymede's fields must remain open to question.

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7. The equations that most simply model the processes of magnetic field generation and convection in a planetary context can be written as

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{U} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B} \quad (1)$$

$$2\Omega \times \mathbf{U} = -\nabla P + \frac{\rho'}{\rho}\mathbf{g} + \frac{1}{\mu\rho}(\nabla \times \mathbf{B}) \times \mathbf{B} + \nu\nabla^2\mathbf{U} \quad (2)$$

where **B** and **U** are the vector magnetic and velocity fields, t is time, η is the magnetic diffusivity, Ω is the vector of rotation, P is the reduced pressure, ρ' is the local deviation from mean density ρ, **g** is the gravity vector, μ is the magnetic permeability, and ν is the kinematic viscosity. When an imposed field $\mathbf{B}_0$ is added to the system, we must in general add three terms to the right sides of the above equations: $\nabla \times (\mathbf{U} \times \mathbf{B}_0)$ to Eq. 1, and $(1/\mu\rho)(\nabla \times \mathbf{B}) \times \mathbf{B}_0$ and $(1/\mu\rho)(\nabla \times \mathbf{B}_0) \times \mathbf{B}$ to Eq. 2. These additional terms destroy the reflectional symmetry $\mathbf{B} \rightarrow -\mathbf{B}$, under which the original equations are invariant. [See, for example, D. Gubbins and K. Zhang, *Phys. Earth Planet. Inter.* **75**, 225 (1993).] The additional (Lorentz) terms in Eq. 2 also provide the system with new possibilities for balancing the Coriolis force (on the left side), which otherwise dominates and inhibits convection.
8. It is important to distinguish between convection-driven dynamos and magnetoconvection. A convection-driven dynamo converts mechanical energy in the form of convective motions into magnetic field energy. For this to occur, the fluid motion must be sufficiently vigorous. This process is most easily described in terms of the modified Rayleigh number—$Ra = g\alpha\beta\mathcal{L}^2/(2\Omega\kappa)$, where g is the acceleration due to gravity, α is the coefficient of thermal expansion, β is the temperature gradient, $\mathcal{L}$ is the characteristic length scale, Ω is the rotation rate, and κ is the thermal diffusivity—whose value determines the strength of the buoyancy force in rapidly rotating systems. As Ra increases from zero, a bifurcation takes the system from a static conductive state to a nonmagnetic convective state at a critical value, $Ra = Ra_c$, say. The strength of the convection thereafter increases with Ra. A magnetic field is only excited at a second critical value $Ra = Ra_m$, say, with $Ra_m > Ra_c$, where another bifurcation takes the system into the magnetic regime. In contrast, magnetoconvection describes convective motions in the presence of, and influenced by, an imposed magnetic field. In this case, the system is already in the magnetic regime, and the initial bifurcation from the conductive state, at $Ra = Ra_c$, leads directly to convection with an associated magnetic field. See, for example, M. R. E. Proctor and A. D. Gilbert, Eds., *Lectures on Solar and Planetary Dynamos* (Cambridge Univ. Press, Cambridge, 1994), for discussions of both these problems of relevance to the present context.
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11. In earlier work [for example, R. Hollerbach and C. A. Jones, *ibid.* **87**, 171 (1995)], it was noted that the relatively stable fields that can develop in a substantial inner core can stabilize otherwise oscillatory or chaotic solutions. In the present problem, the imposed ambient field may play a similar role.
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15. The model used is described in more detail in G. R. Sarson, C. A. Jones, K. Zhang, in preparation.
16. The nondimensional numbers arising in our mean-field model are the Ekman, Roberts, and modified Rayleigh numbers, respectively given by

$$E = \frac{\nu}{2\Omega\mathcal{L}^2}, \qquad q = \frac{\kappa}{\eta}, \qquad Ra = \frac{g\alpha\beta\mathcal{L}^2}{2\Omega\kappa}$$

For numerical convenience we adopt $E = 10^{-3}$, which translates to kinematic viscosities of 6×10^4 m^2 s^{-1} for Io and 8×10^3 m^2 s^{-1} for Ganymede, values that are orders of magnitude greater than even turbulent estimates of these parameters. We have used $q = 2$ for Io and $q = 10$ for Ganymede, these being the smallest values allowing convincing numerical resolution in each case. A more reasonable turbulent value for both models would be $q = 1$. The solutions detailed below were then obtained at $Ra = 170$ for Io and $Ra = 60$ for Ganymede, corresponding to "magnetic Rayleigh" numbers $Ra^* = qRa$—a more useful measure of the vigor of the buoyancy force in this context—of 340 and 600 for Io and Ganymede, respectively.
17. Although at the present stage, models of the satellites' magnetic fields containing nonaxisymmetric features are not available, Cowling's theorem states that purely axisymmetric models are incapable of self-consistent dynamo action [T. G. Cowling, *Mon. Not. R. Astron. Soc.* **94**, 39 (1934)]. Traditional mean-field models circumvent this problem by imposing a so-called α effect, intended as a parameterization of the mean effect of the nonaxisymmetric fluid motions. Our mean-field model avoids this arbitrary step by incorporating nonaxisymmetric fields of a single azimuthal wave number m in addition to the axisymmetric field. At the small values of the Elsasser number $\Lambda = B_0^2/(2\Omega\rho\mu\eta)$, which we model, high wave numbers might be expected to dominate the nonaxisymmetric field. On the other hand, the relatively large magnetic fields internally produced, particularly in the case of Ganymede, result in much larger effective Λ and should lead to smaller preferred m. Here we adopt $m = 4$ as a compromise. Other calculations we performed suggest, however, that the results are not qualitatively changed for different wave numbers.
18. The distinction between toroidal and poloidal fields, and their generation by the ω and α effects, is somewhat more subtle than presented here. See H. K. Moffatt, *Magnetic Field Generation in Electrically Conducting Fluids* (Cambridge Univ. Press, Cambridge, 1978), for a more detailed discussion. It is worth explicitly noting that the presence of the poloidal ambient field, which allows Cowling's theorem to be bypassed (*17*), would allow us to adopt a purely axisymmetric system for our magnetoconvection-type models. Such a system has not yet been considered, however; in the model for Io presented here, the nonaxisymmetric field remains important. The importance of an ambient field in the traditional mean-field context was considered by E. H. Levy [*Proc. Lunar Planet. Sci. Conf.* **10**, 2335 (1979)].
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22. G.R.S., C.A.J., and K.Z. are supported by the U.K. Particle Physics and Astronomy Research Council grants GR/K06495 and GR/L22973.

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