MAGNETIC FIELDS AND THE DETECTABILITY OF BRINE OCEANS IN JUPITER'S ICY SATELLITES; Jeffrey S. Kargel1 and Guy J. Consolmagno2, 1U.S. Geological Survey, Flagstaff, AZ 86001; email jkargel@iflag2.wr.usgs.gov; and 2Vatican Observatory Research Group, University of Arizona, Tucson 85721

Abstract. Salt water's electrical conductivity prompted us to investigate whether electromagnetic induction might occur in a salty ocean in Europa or Ganymede. An ocean could be detected in three ways. (1) Oceanic convection could induce electromagnetic fields or even an internal dynamo. (2) If brine reaches a moon's surface in electrical contact with ambient plasma, then a unipolar current, an induced magnetic field, and Alfvén waves would be set up by Europa's motion through Jupiter's magnetic field. (3) Even if the ocean is electrically insulated from the plasma, Europa's motion through Jupiter's inclined, offset magnetic field causes the strength of the magnetic field sensed by Europa to oscillate by a factor of two every orbit; this would produce oscillatory electric and magnetic fields. Europa and Ganymede might have highly nondipolar, tilted, but very strong magnetic fields.

Introduction. Europa or Ganymede might have an internal structure which includes a molten water-rich mantle (an "ocean") beneath their icy crusts. Consolmagno [1] worked out the possible thicknesses of ice/water layers and noted that "icy satellites [have] both an excess of water and large amounts of soluble minerals"; he compared such layers to the salty oceans of Earth and meteorite leachates. These oceans might be approximated as eutectic 1.65-molar solutions of MgSO4 [2]. The Voyager 1 and 2 flybys renewed interest in possible ice-crusted oceans when they found evidence of ancient cryovolcanism on Ganymede [3] and a fractured ice shell on Europa [3,4]. Europa's crust has large rifts and resembles terrestrial sea ice [5,6]. Tidal and radiogenic heating might maintain liquid water beneath Europa's ice crust [7-10]. A salty ocean probably would not freeze completely even without tidal heating.

Oceanic induction fields of Earth, Uranus, and Neptune. The electrical conductivity of eutectic MgSO4 is 2.5 S m⁻¹ (2.25 x 10¹⁰ cgs units), comparable to that of ocean water on Earth [11-14]. This is 7 orders of magnitude less conductive than pure copper but 6 orders greater than pure water. Earth's ocean currents have a small but measurable effect on the geomagnetic field. The oscillatory tidal component of the oceanic field is 3 x 10⁻⁴ of Earth's total field [15, 16]. Uranus and Neptune may possess deep ice mantles or supercritical "oceans" of water, ammonia, and other volatiles, in which dynamos may generate Uranus' and Neptune's peculiar magnetic fields [17].

Is it possible that brine oceans in Europa or Ganymede, located within Jupiter's magnetosphere, have significant and measurable electromagnetic induction fields? Could an actual magnetic dynamo be generated within such an ocean? A major magnetospheric disturbance in Jupiter's magnetic field was caused by Ganymede and was seen by Voyager 2 from more than 10 Ganymede radii distant [18]. The cause of this disturbance is unknown, but Galileo should be in a much better position to study such disturbances and help us assess their causes.

Calculations. A brine ocean on Europa might consist of a shell of radius 1500 km and thickness of 100 km. Ganymede's ocean might consist of a shell of radius 2500 km and thickness of 100 to 500 km [2].

Convective induction fields. The Magnetic Reynolds Number, Re, relates to how strongly the magnetic field is tied to fluid motions; Re > 1 indicates that the fields are strongly tied to fluid motions, and thus the presence of such a fluid ought to influence any ambient magnetic field. The Magnetic Reynolds Number is:

\[
Re = \frac{4\pi\sigma L v}{c^2},
\]

where \(\sigma\) is the electrical conductivity, \(L\) the characteristic length, \(v\) the characteristic speed, and \(c\) the speed of light.

Radiogenic heat plus tidal dissipative heat generated beneath the ocean would cause heat to flow through the ocean from its base, thereby inducing convection. Dissolved salts suppress the volume-temperature behavior of pure water so that a salty ocean could convect normally. Convective currents in Europa's ocean due to radiogenic heating alone could be \(> 1 \text{ m s}^{-1}\), which we take for \(v\) in the case of convective induction.

Europa and Ganymede have rotation periods of a few days. Their rotation is synchronous, however, so there is no significant relative rotational motion of these satellites with respect to the Jovian magnetic field. The Jovian magnetic field is spinning along with Jupiter in the same direction as but much faster than the satellites' orbital motion. The relative motion of Jupiter's magnetic field past Europa is \(1.04 \times 10^7 \text{ cm s}^{-1}\).

For normal convection in Europa's ocean, \(Re\) is about 0.3, less than but near unity. For the motion of the entire shell through the ambient Jovian field, \(Re = 5 \times 10^5\). A similar calculation for Ganymede, assuming a 100 km thick convecting shell, yields \(Re = 0.3\) and \(1 \times 10^5\). Ganymede may have a salty layer 500 km thick [2], so our depth for Ganymede's ocean may be conservative. We conclude that the induced magnetic field due to these moons' motion could have a noticeable effect on the Jovian field, but that the effect of internal convection is marginal.

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The Dynamo Number, \( N \), is a function of the Magnetic Reynolds Number associated with the nonuniform rotational speed of the convecting fluid and that associated with convection. If \( N \gg 1 \), then a dynamo-driven magnetic field is possible. The Dynamo Number, \( N \), is given as

\[
N = \frac{\gamma I R^3}{\eta^2},
\]

where \( \gamma \) is the fluid rate of global shear; \( I \) the helical component of turbulent convection; \( R \) the scale of the field, which we take to be the radius of the satellite; and \( \eta \) is defined as:

\[
\eta = \frac{c^2 v_{\text{shear}}}{4 \pi \sigma},
\]

where \( c \) is the speed of light, and \( \sigma \) is the electrical conductivity (in cgs units).

To evaluate \( N \), the values of \( \gamma \) and \( I \) must be determined. By definition, \( \gamma = \frac{dV}{dt} - \frac{V}{r} \), where \( V \) is the velocity of the fluid in the \( \phi \) direction and \( r \) is the position inside the moon. For a spinning moon where the primary \( \phi \) component is the convection velocity \( v \) over a convecting thickness layer \( t \), \( dV/dt = 2vR/t \) and \( V/t \) is equal to \( v/R \); the first term dominates when \( t << R \). \( I \) is estimated roughly as \( 0.25x_{\phi} \), where \( x \) is the length of a typical large turbulent eddy (assumed to be 1 km) and \( \omega \) is the known angular velocity of the spinning moon.

We determine \( N \) to be about 4 for Europa and 10 for Ganymede. These values, though small, are greater than unity, indicating a dynamo is marginally possible but not inevitable. The ratio of the polar to toroidal field is roughly the ratio \( I \) to \( \gamma \), which is only ~10^{4} in this case. Any field generated in a brine ocean would be poorly characterized as a dipole centered on the moon, but it should be offset and tilted, and it should have a large non-dipole component.

**Unipolar Field.** If charge can flow from the plasma, through Europa, and into the plasma again, then the motion of Jupiter's corotating field past Europa would set up a \( v \times B \) electric field, resulting in an electrical current.

Jupiter's B field near Europa is 0.004 gauss, and the plasma moves past Europa at by Galileo during close flybys, and Alfven waves might be detectable farther away. Characterized as a dipole centered on the moon, but it should be offset and tilted, and it should have a large non-dipole component. The electrical current would be the product of the brine's conductivity and the \( v \times B \) electric field, or \( E = vXB/c \). The resulting current density would be the product of the brine's conductivity and the \( E \) field, or \( 3 \times 10^4 \text{ esu/cm}^2 \). Such a current, however, would produce a magnetic field strong enough to cancel (by Lenz's Law) the ambient jovian B field, shutting down the system. A more realistic value for the internal field, following Sonett [19], is about half the ambient field. Cancellation of Jupiter's ambient field near Europa would be readily discerned by Galileo during close flybys, and Alfven waves might be detectable farther away.

**Oscillating current.** If an electrical connection between the plasma and an ocean is lacking (due to an intervening insulating ice crust), then the satellite's motion effectively turns it into a capacitor. However, the change in the B field also creates an E field (following one of Maxwell's equations), such that \( (1/c)(dB/dt) = dE/dx \), where the oscillation in B occurs with the relative corotation of Jupiter's field; the change in E occurs over a distance taken as the size of a conducting shell inside the moon. For Europa, we calculate \( E = 2 \times 10^{-10} \) in cgs units; the resulting current is 5 esu/cm², still sufficient to create a field that would cancel Jupiter's ambient B field. As above, such an induced field would reduce the local jovian field that Europa sees, so that the real field may be about half the ambient jovian field (i.e., ~0.002 gauss). The arguments above still hold, except that now the strength and direction of the field oscillates in time with a period equal to the rotation period of the jovian plasma past Europa.

**Conclusions.** Galileo might find that Europa and Ganymede have fully developed magnetospheres embedded within Jupiter's; alternatively, these satellites' induced magnetic fields may modulate Jupiter's local field. An ocean-generated magnetic field may be tilted and offset from the rotation axis, and it may have a large non-dipole component and rapid spatial and temporal variability or stable oscillations. If these variations can be discriminated from those in the ambient jovian field, then the detection of a magnetic induction field of any of the icy Galilean satellites could be taken as evidence for an ocean. The model is not robust enough to rule out an ocean if no intrinsic magnetic field is detected by Galileo near Europa and Ganymede. But a negative observation could be taken as weak evidence against an ocean, or it could be used to derive an upper limit on the ocean's depth.

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**References.**