induced magnetic fields as evidence for subsurface oceans in Europe and Callisto


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The Galileo spacecraft has been orbiting Jupiter since 12 December 1995. The spacecraft has encountered one of the four gaseous satellites—Europe, Ganymede and Callisto—on three orbit. Initial results from the spacecraft’s magnetometer12 have indicated that neither Europe nor Callisto has an appreciable internal magnetic field, in contrast to Ganymede and possibly Io. Here we report perturbations of the external magnetic fields (associated with Jupiter’s inner magnetospheres) in the vicinity of both Europe and Callisto. We interpret these perturbations as arising from induced magnetic fields, generated by the moons in the regions of the periodically varying plasma environment. Electromagnetic induction requires eddy currents to flow within the moons, and our calculations show that the most probable explanation is that there are layers of significant electrical conductivity just beneath the surfaces of both moons. We argue that these treating conducting layers may be explained by the presence of salty liquid-water oceans, for which there is already indirect geological evidence in the case of Europa. Our insight into the source of the magnetic perturbations

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Figure 1 shows the strong fields experienced by Europa and Callisto. Near the corotation of the satellites (the orbit of Europa is closer in Jupiter’s spin equator at Lp/2p and 3p/2p, respectively, but remote from the actual satellite locations, the sources of magnetic field are the internal third dipole of Jupiter and the current flowing in the magnetospheric plasma sheet. The 0°/180° field in Jupiter’s spin and dipole axes implies that the magnetic equatorial plane and the orbital planes of the moons are inclined relative to each other in a coordinate system with the x axis along the direction of plasma convection, the y axis oriented toward Jupiter, and the z axis along the spin axis of the moon. The dip component remains essentially constant. However, the z component of the magnetospheric field varies with the synodic period of Jupiter’s rotation (11.9° for Europa and 10.7° for Callisto) as indicated in the plots. The elliptically polarized variation of the magnetic field (r = 117) in Open circles mark the field values corresponding to the E4 and E14 flybys. The shortest linearity polarized variation of the magnetic field (r = 17) in C. Open circles mark the field values corresponding to the C3 and C7 flybys. The time, altitude and latitude relative to the moon’s equator for these four passes were: E4, 15 November 1996 (65.8°S, 68.4°E); E14, 14 November 1996 (48.1°S, 64.6°W); C3, 15 November 1996 (68.1°S, 92.1°W); C7, 16 November 1996 (32.1°S, 79.1°W). The expected background field was calculated from an empirical model of Jupiter’s magnetospheric field that uses spherical harmonics of order 3 to describe the internal field and an Solar potential formula26 to describe the external field from the 4-growth sheet.

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**Figure 2** Magnetic field observations for the E14 pass. The plot covers a time interval of 77 min during which the spacecraft moved inward from an initial range of 13 Rₚ to ~ 3 Rₚ at closest approach (C₁₄) and traveled back out to a distance of 5.6Rₚ from Europa (here Rₚ is the radius of Europa). The observed magnetic field components (and magnitude in nT) are plotted as thick solid lines. The thin solid lines represent the estimated background field of Jupiter's magnetosphere along Galileo's trajectory, estimated from the interpolation of magnetic data obtained along the trajectory when the spacecraft was sufficiently far from Europa (~10 Rₚ) that the induction and plasma interaction effects were negligible. The modeled field (induction + background) is shown by dotted lines, and provides a satisfactory fit to the large-scale field variations. Field circles show the observations corrected for the plasma pick-up effect described in the text, and this correction is seen to improve the agreement. The variables x, y, and z shown under the figure describe the trajectory of the spacecraft in the coordinate system described in Fig. 1 legend. It is the range of the spacecraft. All distances are in units of Rₚ (Rₚ = radius of Europa = 1821 km). The data sampling rate changes from 30 Hz to 144 Hz to 6.2 Hz to 2.5 Hz to 1 Hz. The reduced modeled field used here and in Fig. 3 was calculated using the equations $B_x = B_x' + a(R_x/R_c)\hat{R}$, $B_y = B_y' + a(R_y/R_c)\hat{R}$, and $B_z = B_z'$, where $B_x$, $B_y$, and $B_z$ are the components of magnetic field in a spherical coordinate system which has a pole direction antiparallel to the background field $B'_0$.
of flow by the conducting obstacle and associated plasma effects. As the component of the magnetic field \(B_\parallel\) along the flow direction is small \((\frac{B_\parallel}{B} < 1)\) for all the encounters, plasma effects will be symmetric about a plane through the centre of the moon, perpendicular to the background magnetic field. Above and below this plane, plasma currents drape the field around the moon, causing bending. In the symmetry plane, near which these observations were made, plasma effects change the field strength without changing its orientation. If the orientation of the field is not to change, each component must change by the same fractional amount: \(B_\parallel / B \approx B / B \approx 0 / B\). Here \(R_P\) is the change in the field strength. Thus, by reducing each component by a factor \((1 - \frac{B_\parallel}{B})\), we can approximately remove the plasma contributions. The correction improves the agreement between the observations we model for the both E14 and E4 (not shown here) fly-bys.

At Callisto, corrections for plasma effects are not needed. Figure 3 shows the observed perturbations and the induced dipole model for the C3 and C9 passes: agreement is good. As these Callisto encounters occurred opposite phases of the variation of the background field (away from Jupiter for the C3 fly-by and towards Jupiter for C9), the induced dipole moments were roughly antiparallel (see Fig. 3a and b). This convincingly demonstrates that the Callisto oscillations cannot be explained by a fixed internal dipole.

For the multiple Europa observations, the orientation of the time- varying component of Jupiter's field changed only slightly during the relevant passes, so the induced dipole moments differed only slightly. A fixed internal dipole cannot be excluded, although its orientation at a large angle to the spin axis seems improbable.

The induced-field model for Europa and Callisto constrain their interior structures by requiring conducting paths \(\alpha\) or near the surfaces. It is known that a periodically varying magnetic field (angular frequency \(\omega\)) acting on an electrically conducting object of conductivity \(\sigma\) decays in an \(\approx\) folding length of \(S = (\omega\tau)^{-2/3}\); here \(S\) is the skin depth and \(\tau\) is the permeability of the period of the wave is \(1/\eta\) and the conductivity is \(1/\mu - 5\). The threshold for a spherical shell can be expressed in terms of bush functions, but when the thickness of the conducting layer \(0 < 0.1\) and 5 < 0\( \eta < S\), the energy dissipated in the shell is \(\approx 10^5\). The development of the induced dipole field (whose surface field at the pole is quite opposite and is null in the geophysical field) (see Fig. 2 legend). The observed amplitudes of the induced signatures of Europa and Callisto require conducting layers of depth \(\approx 0.1\) near the surfaces. For Europa, an obvious candidate for conducting paths is its ionosphere \(\approx 100\) or a cloud of ionized \(\eta\). However, estimates of the conductivities of these gases give smaller values; thus, the required wave much larger than the moon itself. Thus the wave quickly penetrates the ionosphere without causing significant induction. Skin effects (for an approximately non-zero \(\tau\)) of various materials likely to be found in the icy outer layers of Europa or Callisto can be determined. A realistic model of (\(\omega\)) and \(\mu\) would have a skin depth greater than \(10^8\) km. Metal such as iron are not expected to be abundant in the outer layers of a differentiated body. Induction from inner metallic cores can also be ruled out. A metallic core whose radius is half the moon's radius would produce a signature that is only one-slight as large observed because the induced dipole field magnitude falls as inverse distance. I even an ocean whose salinity is comparable to Earth's ocean could produce the signature. The conductivity of Earth's ocean water (salinity \(3.79\)) is \(\approx 2.75\) \(m\) at 0°C. Thus Earth-like oceans with thicknesses \(\geq 10^8\) cm could generate the observed signatures in Europa and Callisto. The conductivity of ocean water is electrically conductive and requires only small amounts (a few percent) of dissolved salts (like \(\text{NaCl}\)) or acids (like \(\text{H}_2\text{SO}_4\)) that hydrolyze readily.

Induced fields at Europa have been considered \(\approx 200\) \(m\), followed by \(\approx 2000\) recent speculations \(\approx 2007\). Neubauer \(\approx 2007\) noted that the published \(\approx 2007\) moments of the magnetic field perturbations near Europa and Callisto could be fully or partially explains the induction from sub surface ocean on or ice layers near the melting point. The possibility of a liquid–water ocean beneath the icy surface of Europa has been debated for many over two decades. Accretional and radiogenic heat sources are large enough to dehydrate the interior of Europa early in its evolution, leaving the moon covered with a layer of liquid water \(\approx 100\) km thick. Measurements by the Galileo Galileo of Europa's gravitational field show that Europa is strongly differentiated (with a metallic core), and that indeed has a water–ice–liquid layer \(\approx 100\) km thick.

Thermal models considered only the conductive cooling and freezing with time of the outer layer or water, and predicted that at present liquid water existed beneath on ice shell. It was later shown that with thickening, the outer layer of ice would become unstable to thermal convection, promoting heat transfer through the ice and solidification of the underlying water. Complete freezing of the outer layer of water in a small fraction of geological time is possible but not certain, even for pure water. Additional, tidal dissipation in Europa's ice shell provides a heat source that could offset the conductive cooling of the ice and prevent complete solidification of the water ocean.

The competition between the tendency of tidal heating to maintain a liquid water ocean and that of ice convection to freeze the ocean has been analyzed, but a definitive conclusion was not reached. Significant uncertainties include the unknown rheology of ice and the dependence of the thermal conductivity on ice on its temperature and physical state. A thermally insulating surface layer would prevent stabilization of a liquid-water ocean. The occurrence of minuscule-inhabitants in the ice and ocean, such as salts and ammonia, would affect the rheology of the ice and the freezing temperature of the ocean. Tidal heating of the main moons in the ice and frictional dissipation due to forced circulation in the liquid–water ocean may be important.
Quantized conductance through individual rows of suspended gold atoms

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As the scale of microelectronic engineering continues to shrink, interest has focused on the nature of electron transport through essentially one-dimensional nanometer-scale channels such as quantum wires* and carbon nanotubes**. Quantum point contacts (QPCs) are structures (generally metallic) in which 'nodes' of atoms just a few atomic diameters wide (that is, comparable to the conduction electrons' Fermi wavelength) bridges two electrical contacts. They can be prepared by contacting a metal surface with a scanning tunnelling microscope (STM)** and by other methods***, and typically display a conductance quantized in steps of 2e²/h or 1.55 x 10¹⁵ A/V, where e is the electron charge and h is Planck's constant. Here we report conductance measurements on metal QPCs prepared with an STM that we can simultaneously image using an ultrahigh-vacuum electron microscope, which allows direct observation of the relation between electron transport and structure. We observe strands of gold atoms that are about one nanometre long and a single chain of gold atoms suspended between the electrodes. We can thus verify that the conductance of a single strand of atoms is 2e²/h and that the conductance of a double strand is twice as large, showing that...