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Physics can have some of the most unique and extraordinary applications of basic principles applied on a larger scale. This paper will explore the properties of induced magnetic dipoles and will examine this phenomenon directly from Jupiter's moon, Europa. These properties will be used to determine if there is liquid water beneath its icy surface and how this conclusion was verified. This will be accomplished using the concepts of magnetic dipoles and induced currents. Recent missions have also revealed estimates of the depth of Europa's subsurface ocean. There have been many measurements taken of Europa's magnetic field, and they are the most important variable in determining the depth of the Europan ocean depth. The relation between the magnetic dipole measurements and the ocean depth will be shown in figures.

I. STUDY PURPOSE

The purpose of this paper is to show the existence of a subsurface ocean beneath Europa's surface and make an approximation of how deep the liquid ocean must be. This will be based on basic physical principles, namely of magnetic fields and their interactions, that can be very useful and lead to important discoveries. There will be a necessary amount of assumptions, such as those involving the magnetic field around Jupiter, that penetrate Europa to be relatively constant and that all relevant celestial bodies are to be close to perfect spheres. These assumptions will be vital as they directly correlate to the calculations performed.

II. THE CONCEPT OF MAGNETIC FIELDS

The solar system is abundant with magnetic fields around celestial bodies. The easiest magnetic field to measure directly is the Earth's. The field is caused by a dynamo action involving Earth's molten magma layers. [4] As the Earth rotates about its axis, molten layers rotate at a different rate due in part to convection properties and the Coriolis Effect. This motion generates a large electric current, which is responsible for why the magnetic field around Earth is so strong as it can withstand the majority of charged particles from the sun. It is worth noting that the Dynamo Theory is an ongoing field of research that does not have a solid basis yet, but it is theorized based on observations with the Earth and Venus that it is correlated to the rotation rate and the motion of fluid metallic iron. [10]
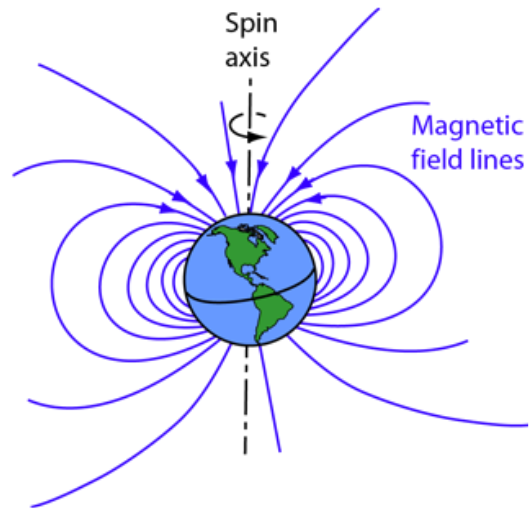

FIG. 1. [10] Earth's magnetic field is relatively stable, though it does not line up directly with its rotation axis. The existence of a strong magnetic field to deflect oncoming charged particles from the sun is vital for the existence of a thick atmosphere, or else the Earth would have suffered a similar fate to the Martian atmosphere where the outer layers would be stripped away by solar winds.

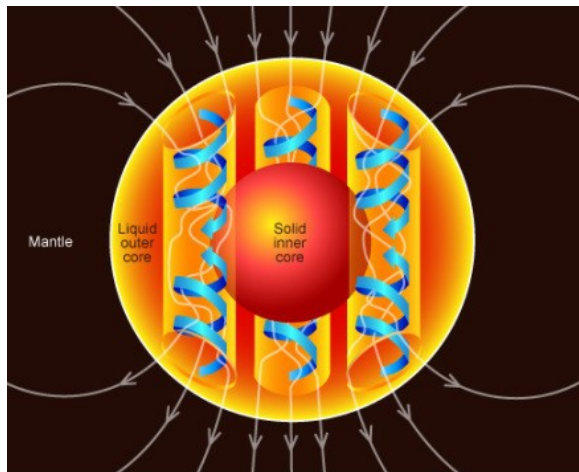* francil4@my.erau.edu; zanolinm@erau.edu

FIG. 2. [15] The dynamo action responsible for the Earth's magnetic field is based on the convection and motion of the liquid outer core of the Earth. If the entirety of the core was solid, then this action would cease and the magnetic field would not exist. [10]

Most definitely, not all planets generate their magnetic fields this way, [4] but measurements taken on Earth can be used as a "control group" for other satellites, and the way that the field is generated can be then inferred to other fields found on other solar system bodies, unless further evidence proves otherwise.

III. JUPITER'S MAGNETIC FIELD

Jupiter possesses the strongest planetary magnetic field of the entire solar system; overall, it is second to only the sun itself. [5] Unlike Earth, Jupiter's field, known as the Jovian field, does not deride from convective liquid magma. Rather, it is created by a rapidly spinning layer of metallic hydrogen. [4] The magnitude of the field can be up to ten times that of Earth's, and the rapid motion of the hydrogen layers can make the field more complex. The Jovian field still exhibits the property that there are two poles that output a relatively constant strength of magnetic influence as it rotates about itself. However, recent observations show that Jupiter could possibly be going through a pole shift because the magnetic flux calculated as expected north and south regions located at the poles but also an additional south region near the equator. [16] As the magnetic field is measured farther away from the Jovian surface, it begins to act more like a uniform magnetic field as expected. There is still much speculation on how the Jovian field itself is formed and magnetic fields in general, [4][16] but this paper is not concerned with how they are formed. For the purpose of this research, the magnetic field that penetrates Europa will be treated as uniform.
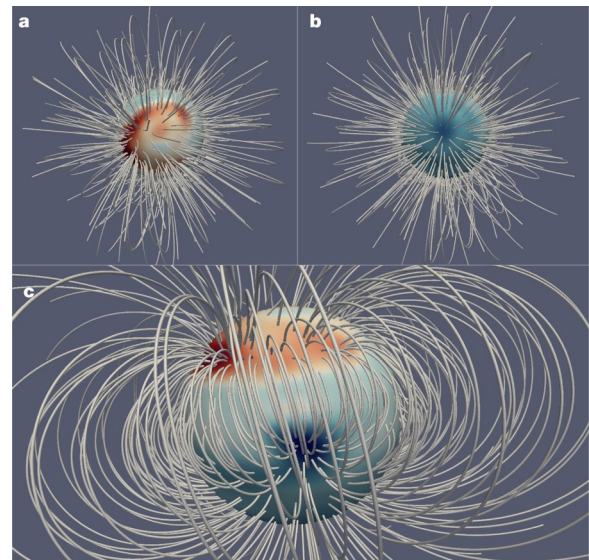

FIG. 3. [16] The top left (a) and top right (b) show the invisible magnetic field lines of Jupiter where the red represents northern regions and blue is the southern regions. Bottom shows an additional southern pole near the equator, which appears to be a unique occurrence not found anywhere else in the solar system yet.
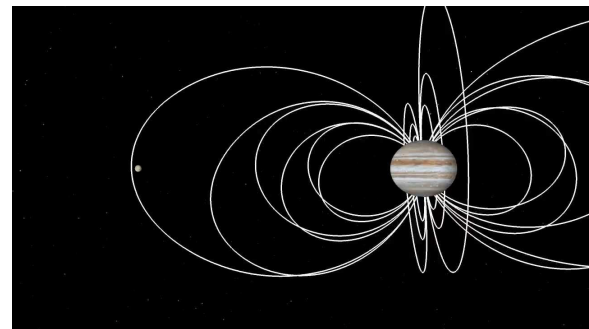

FIG. 4. [6] Magnetic field lines about the poles of Jupiter rotating about its axis and intercepting Europa (seen to the left). Europa orbits at a distance far enough so that the fields can be treated as uniform for calculation.

IV. EUROPA'S INDUCED MAGNETIC DIPOLE

Jupiter's 6th moon, Europa, at first glance is similar to other Jovian satellites. Roughly the size of Mercury, it is tide-locked to Jupiter and is remarkably covered in a solid layer of water ice. [14] Its most notable features are its surface cracks, indicating that there has been some sort of motion on the surface due to changing temperatures. Proposed reasons include the heat originating from tidal forces to tectonic activity due to the tidal forces it receives from orbiting in an elliptical pattern. [14] However, recent observations of ice "turning over", localized

areas of heat, and water plumes indicate that it could be due to convective activity beneath the surface. [9] If this is true, then that is a strong indication that there could exist a layer of liquid water beneath its ice. The tidal forces themselves could also be enough of a heat source to generate liquid water. However, there must be conclusive evidence of the liquid water's existence. This is where the Jovian magnetic field can be applied.

Because of Europa's size and makeup, it would be near to impossible for it to create a magnetic field of its own based on current Dynamo Theory. Europa is theorized to have an iron core and rocky mantle, so no current would flow and generate a magnetic field. [14] However, during the Galileo Mission (1995-2003), it was reported that Europa had disrupted the Jovian magnetic field in which the moon "bent" the otherwise uniform Jovian field. [2] This is important because it implies that Europa itself is not creating a magnetic field, yet one is clearly present and observable. Therefore, the Jovian field is creating an induced current which in turn creates an induced magnetic dipole around Europa. It is also likely to be specifically an induced magnetic field because the Europa's field was in the wrong direction, which matches what happens when a magnetic field induces a conductor. [1] It is determined that the most likely explanation for the induced magnetic field is a global ocean of salt water. [2]
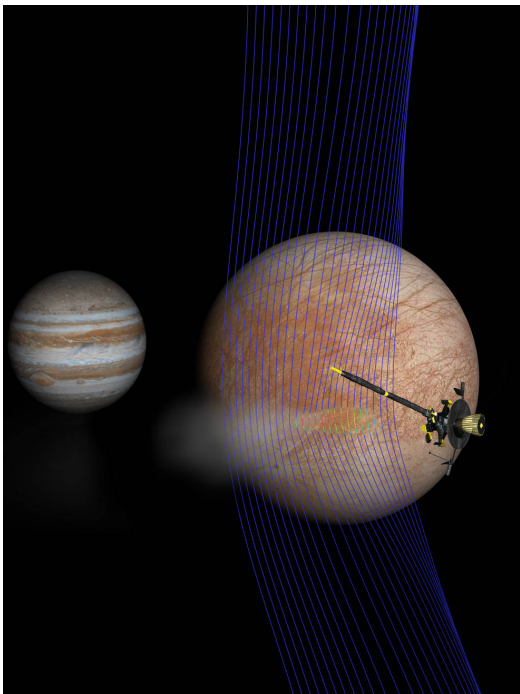

FIG. 5. [9] The figure above demonstrates the effects of an ice plume from Europa. The lines represent the pathway of the plume particles, but they should not bend as drastically as predicted. Europa does not have the capacity to produce a magnetic field of its own. [14] Thus, it must be induced.

The only source of a magnetic influence similar to the one measured is an induced current. Just as an electric current generates a magnetic field around it, so does a strong enough changing magnetic field create an induced current. [2] However, this is only true in material that can easily conduct a flow of charges, making the current possible. If a magnet is moving along a solid block of concrete, for example, then there is virtually no current induced since the electrons within the material have no possible way to flow. The Jovian field should be strong enough to create induced currents within objects in its close proximity, as long as they can conduct. If a large body is able to conduct this current, then a small magnetic field is generated from the induced current. This is known as an induced magnetic dipole, and it interferes with the larger Jovian field within close proximity to itself. For all intents and purposes, Europa should not be able to conduct enough current to disrupt a fair magnitude of the Jovian magnetic influence. The only conductor that could do this would be a highly-ionized liquid ocean, in this case salty water. [1] This is highly viable evidence for the existence of a global liquid water ocean beneath the thick ice layers. Observations of the induced magnetic field is not easy, namely because the Jovian magnetic field is so strong that it can fling high energy particles towards operating spacecraft as well as flowing charged plasma. [11] Even so, there have been a number of successful observations that point to the existence of a salty liquid submerged ocean. The questions remain of how thick the ocean layer is and what is its exact composition, because there is a limit of uncertainty to both of those factors.

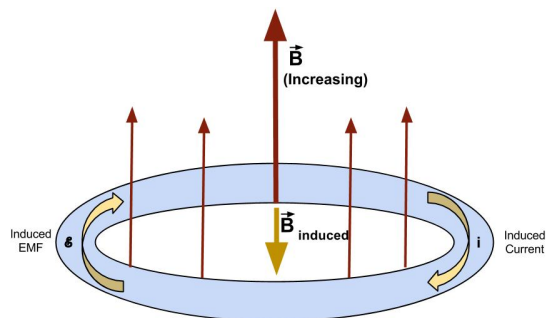## V. THE DEPTHS OF EUROPA'S ION-RICH LIQUID OCEAN

FIG. 6. [7] In this example, the brown B field in the upper direction represents the uniform magnetic field that is always present, which induces a current that moves counterclockwise when viewed from above. Once there is enough current, the induced B field attempts to counteract the original B field in the opposite direction in the center.

It is necessary to first show how the strength and direction of a magnetic dipole is formed. The equation for

any given magnetic dipole induced by a magnetic dipole moment $\boldsymbol{m}$ is

$$\boldsymbol{B}_{dip}(\boldsymbol{r}) = \frac{\mu_0}{4\pi}[3(\boldsymbol{r}\cdot\boldsymbol{m})\boldsymbol{r} - r^2\boldsymbol{m}]\frac{1}{r^5} \qquad (1)$$

[13]

Where μ_0 is the permittivity of free space and $\boldsymbol{r}$ is the directional distance from the magnetic dipole moment. This can be rearranged and written in a more simplistic way:

$$\boldsymbol{B}_{dip}(\boldsymbol{r}) = \frac{\mu_0}{4\pi}\frac{1}{r^3}[3(\boldsymbol{m}\cdot\hat{\boldsymbol{r}})\hat{\boldsymbol{r}} - \boldsymbol{m}] \qquad (2)$$

[3]

This is the coordinate free form of a magnetic field of a dipole. Both equations are dimensionally consistent. It is also possible to rewrite this in terms of spherical coordinates:

$$\boldsymbol{B}_{dip}(\boldsymbol{r}) = \frac{\mu_0 m}{4\pi r^3}[2\cos\theta\hat{\boldsymbol{r}} + \sin\theta\hat{\boldsymbol{\theta}}] \qquad (3)$$

[3]

These formulas would calculate an induced magnetic dipole in a free system with no outside interference. However, it is difficult to calculate the induced magnetic field explicitly as there are a number of perturbations and variables that can affect the measurements, such as the conductivity and salinity of the ocean, the thickness of the Europan ice sheet, and the direction of the spacecraft flyby. Therefore, it is necessary to look at the actual measurements made from the Galileo mission in order to better understand these limitations:
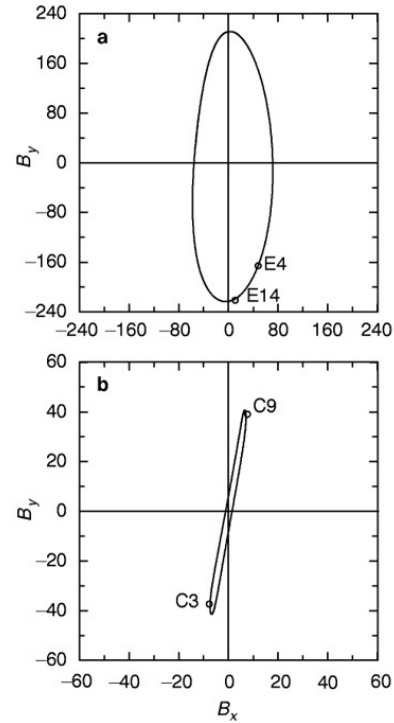

FIG. 7. [7] These figures a and b represent the varying magnetic fields by Europa and Callisto respectively. Note that Callisto does not vary nearly as much as Europa's. The z axis is the orientation of the moon's orbit, and the values represent the average change of the magnetic flux density in nanotesla's or nT.

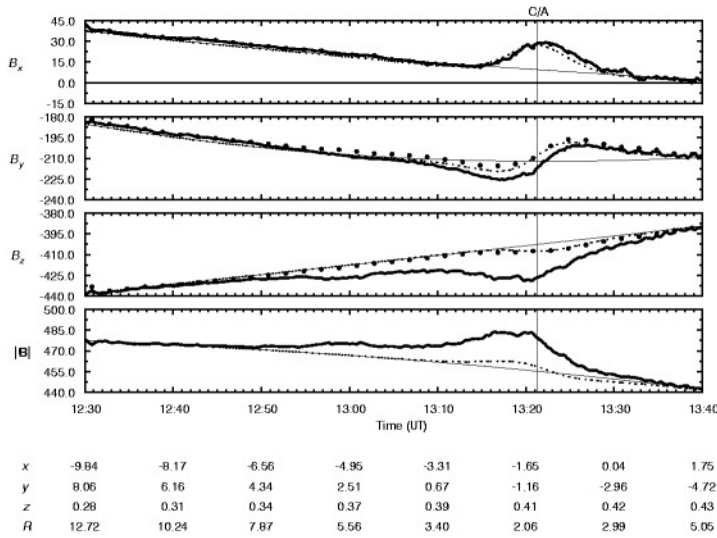|								
x	-9.84	-8.17	-6.56	-4.95	-3.31	-1.65	0.04	1.75
y	8.06	6.16	4.34	2.51	0.67	-1.16	-2.96	-4.72
z	0.28	0.31	0.34	0.37	0.39	0.41	0.42	0.43
R	12.72	10.24	7.87	5.56	3.40	2.06	2.99	5.05

FIG. 8. [7] These are the specific values of the measured magnetic flux densities (dark black lines) measured against the Jovian background field (thin solid lines) as a function of time. The dotted lines are the modified fields, and the black dots represent observations corrected for the plasma pick-up effect. The units are again in nT, and C/A represents the satellite's closest approach. The variables x, y, and z describe the satellite's trajectory and position, and R is the range of the craft, all measured in Europa Radii ($1 R_E = 1,560 km$).
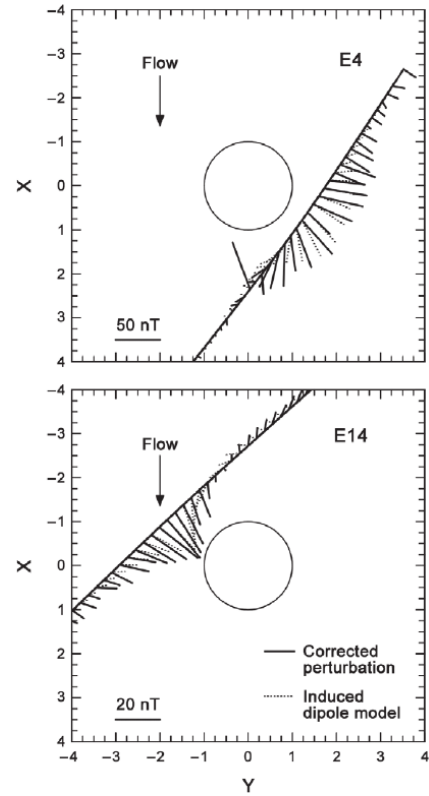

FIG. 9. [12] The dark black lines represent the vector perturbations in the magnetic field near Europa measured by Galileo during the E4 and E14 flybys. These are compared to those vectors expected from induction from a global perfect conductor, shown in dashed lines. The z direction is assumed to be the orbital axis of Europa, and the x and y axis are measured in Europan Radii.
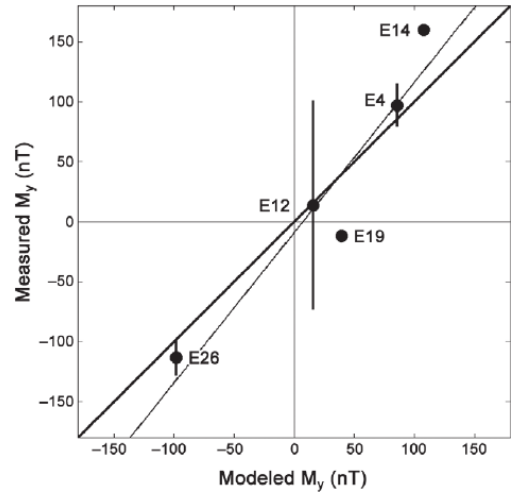

FIG. 10. [12] In this case, the y-component alone of the induced dipole moment measured during five flybys of Galileo. The dark line is the measured induced dipole moment, and the thin line is the modeled dipole moment.
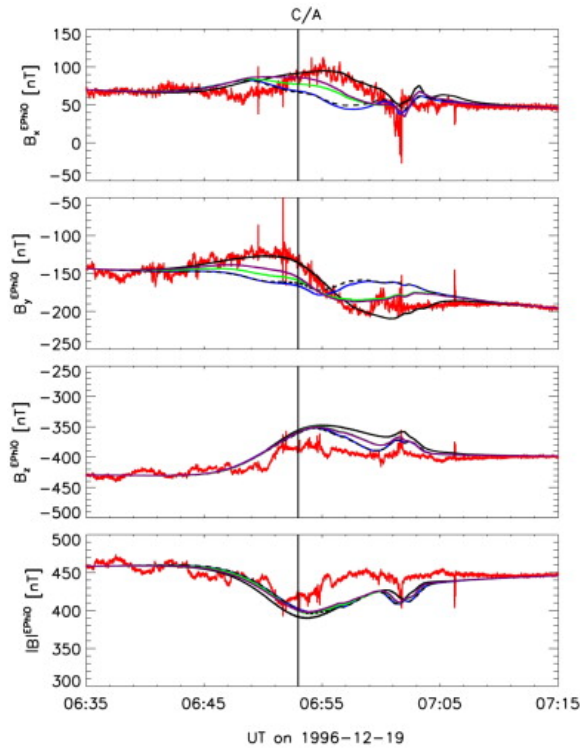
FIG. 11. [13] This portrays the observed and modeled magnetic fields from the E4 flyby in the EPhiO coordinate system. Top to bottom shows the measurements of B_x, B_y, B_z, and B_m. The dashed black curve represents no induced magnetic dipole from Europa (simply a Jovian field), and the predicted magnetic fields with the induced dipole are plotted assuming an ocean conductivity σ of $100mS/m$ (blue), $250mS/m$ (brown), $500mS/m$ (green), and $5S/m$ (black). This is also assuming the ocean crust is 25 km and the assumed thickness of the ocean is also 25 km.
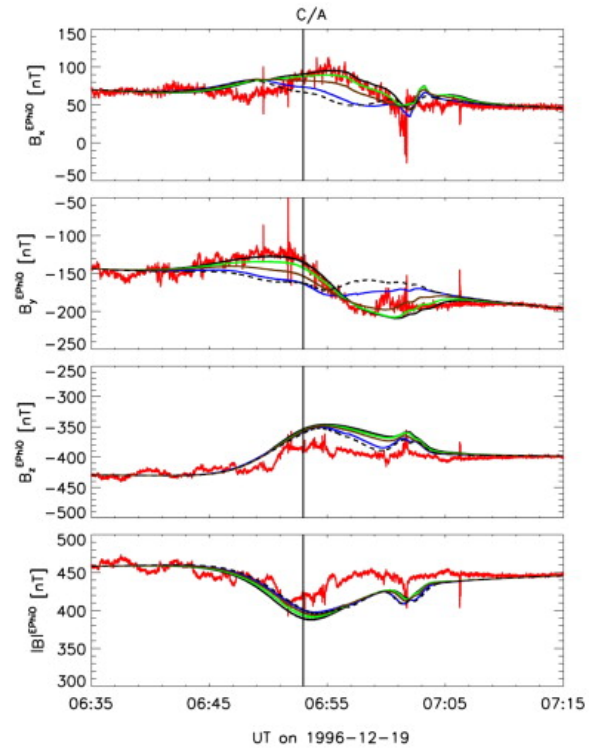
FIG. 12. [13] This graph is the same format as FIG. 11, but the assumed thickness of the ocean is now 100 km. All other parameters are the same, but the results are different if one assumes a larger ocean altogether.
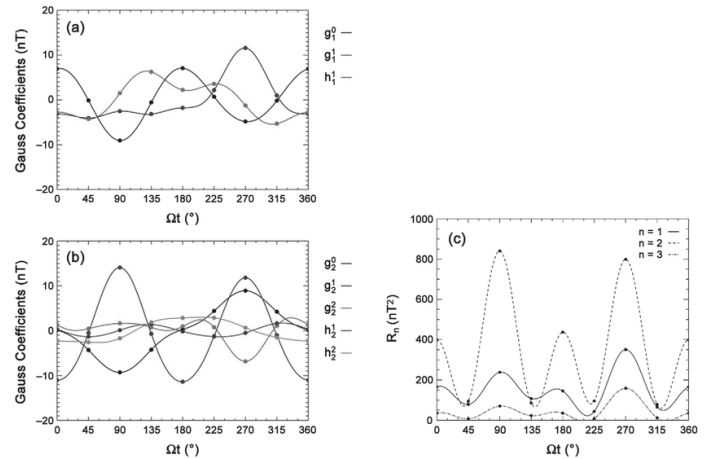

FIG. 13. [12] As the spacecraft is in an orbit around Jupiter, this graph represents the measured plasma interaction from Europa with regards to its induced dipolar (a) and quadrapolar (b) terms. (c) shows the total power contained in the induced field at the first three spherical harmonics, which can be estimated to be the total induced magnetic field.
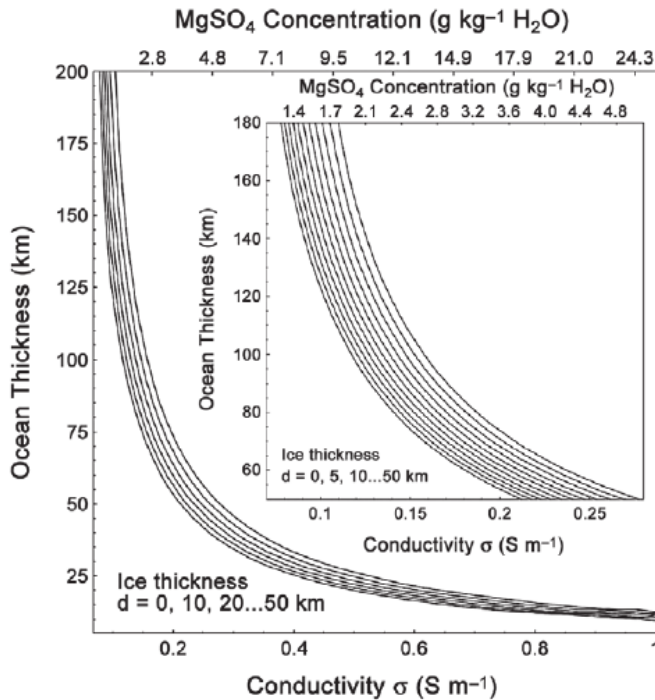
FIG. 14. [12] There has been some potential evidence that the salt composition contains a fair concentration of $MgSO_4$ [12]. These separate curves were calculated with different ice thickness assumptions, and the comparisons were plotted.
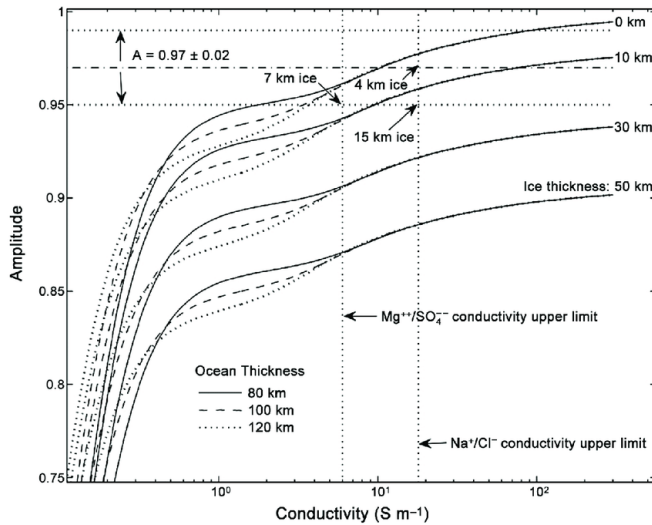

FIG. 15. [12] This shows the strength of the magnetic induction response as a function of 3 variables: conductivity (x-axis), ocean thickness (separate lines), and ice shell thickness (represented by the solid, dashed, and dotted lines). These allow for a fair range of values of the true ocean depth, and it is clear that limiting the values of a single variable can help estimate the ocean depth to a much better degree.

Therefore, it can be shown that the primary issue with

estimating the depth of the Europan subsurface ocean is that the exact composition, and thus the conductivity, is unknown, so therefore there is a large range of depth lengths that the ocean could be, even if the exact magnitudes of the magnetic field are well-known.

VI. FUTURE OBSERVATIONS AND IMPLICATIONS

There is, however, some good news on the progress of this scientific project. On May 26, 2015, NASA announced a selection of ICEMAG, MISE, and 7 other investigations for near future Europan science investigations. [2] ICEMAG, which stands for Interior Characterization of Europa using Magnetometry, will be an instrument that can observe the magnetic field with far more sensitivity than the previous Galileo spacecraft. [2] This data collected will be compared along the other instrument, known as MISE or Mapping Imaging Spectrometer for Europa, that will use spectroscopic emissions to determine the surface composition and infer the liquid salinity. [2] It may also offer some input on the ice shell thickness, which is also a contributing factor to the overall calculations for the ocean depth. The missions will be sent there by the 2020's decade, and the data it receives will create much more clarity of the exact range of depths of Europa's subsurface ocean.

VII.   CONCLUSION

It is the overwhelming scientific consensus that there is most likely a liquid, salty ocean of water beneath the surface of Europa. What is yet to be determined is the depth of the ocean itself and the total salinity, but new missions may soon take samples of the ice surface and determine what composition of ions are present and the total salinity of the ocean. Table salt is just one example of the many ions that can be present in an ocean, and the exact composition is yet to be determined. Depending on what information about this is found in the future, more constrained ranges for the ocean depth can give scientists a better understanding of the true depth of its magnificent ocean and perhaps the very nature of the ingredients for bio-genesis.

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