

The iron snow dynamo theory for Ganymede

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Ganymede is the largest moon in the solar system (figure 1). With a radius of 2,634 km, Ganymede is slightly larger than the planet Mercury.¹ A unique feature of Ganymede is that it possesses its own intrinsic magnetic field. To planetary scientists, it has been a challenge explaining how an object of Ganymede's size could still possess its own magnetic field after over 4 Ga. After billions of years, an object of Ganymede's size would be expected to have cooled down so that there would not be adequate heat to drive a magnetic dynamo. A dynamo requires a molten iron core that can have a convection motion of the fluid, which carries an electric current. But for Ganymede the iron core is only approximately 700–800 km in radius. Ganymede may not have a solid iron core, but has a liquid iron core surrounded by a silicate mantle, and then layers of water ice over the mantle.

Ganymede is influenced by the strong magnetic field of Jupiter, but there is a good consensus among scientists that it possesses its own intrinsic field.^{2–4} The *Galileo* spacecraft conducted magnetometer measurements which have been analyzed in relation to Jupiter's field. Ganymede's main dipole field was measured as 719 nanotesla (nT) and is tilted 176° in relation to its own spin axis.⁵ This makes it roughly antiparallel to Jupiter's magnetic field.

Radioactive heat sources and tidal dissipation have been considered for Ganymede and found to be inadequate to sustain fluid convection in the core. Tidal dissipation is not

significant in heating Ganymede since it is much farther from Jupiter than Io, for example. Scientists have also attempted to make tidal heating a greater heat source in the past by proposing Ganymede's orbit passed through a different orbit resonance in the past that increased the tidal effects. But this research found that tidal heating was inadequate.³ These issues have prompted scientists to look into other mechanisms that could drive a magnetic dynamo for Ganymede. The fundamental question is: how could its magnetic field last to the present, after over 4 Ga of solar system history?

Compositional convection

Recent research from planetary scientists has developed the concepts of what is called compositional convection for driving a magnetic dynamo.^{4–8} When an iron core is mentioned by scientists, the word 'iron' is not usually intended to mean pure iron. It is normally assumed that an iron core consists of some pure iron and some other compound of iron, such as iron sulfide (FeS). In the outer solar system, accepted theories for the formation of the planets and moons would assume that sulfur would be more abundant in the Jupiter region than it would be near Mercury or Earth, for example. Also, iron sulfide has the effect of lowering the melting temperature of the mixture, compared to pure iron. Thus, it is proposed that inside the liquid core, after its formation, a composition gradient would form with more pure iron near the core-mantle boundary and more iron sulfide at the bottom of the core. The mantle is at a cooler temperature and so it cools the top of the liquid core. But since the bottom of the core is under greater pressure, it is hotter. The temperatures of a liquid core for an object the size of Ganymede would be somewhat lower than for a larger object such as Earth's core.

Iron sulfide is less dense than pure iron, so the above situation is unstable. The iron which is cooled near the core-mantle boundary (CMB) can crystallize as small particles (iron 'snow') and sink down toward the bottom of the core. This is the 'snow zone' shown as black in figure 2. Since the temperature increases with depth, the sinking iron 'snow' particles remelt, and this lower liquid zone is where it is proposed convection could take place. The iron sulfide rises toward the top of the core due to its buoyancy. The temperature and pressure conditions and composition of the core mixture determine how the core changes over time.

As the liquid core cools slowly over time, this leads to a growing iron 'snow' layer at the top of the core, which grows downward. Eventually the iron 'snow zone' grows to include all of the core. But while the molten layer exists, it is thought that convection can occur under the 'snow zone'. Thus, it is believed convection currents can form in the molten portion below the iron 'snow zone'. This scenario is a top-down change in the core. The lower liquid zone would eventually be replaced with the 'snow zone', consisting of a mix of solid and liquid. This would stop the convection currents, and a dynamo would stop operating.



Figure 1. Ganymede

Image: NOAA / Public Domain

Scientists have suggested Ganymede originally formed partially undifferentiated and remained that way for some time, so initially there was no iron core. Then only after heat built up later did Ganymede's core form. This would make the core a late feature, so that it does not have to have existed the entire 4.5 Ga since the alleged beginning of the solar system. One study pointed out the iron 'snow' scenario presents a problem because of the limited time required for the 'snow zone' to fill the core:

"Such a dynamo ceases as soon as the snow zone encompasses the entire core, i.e. the dynamo lifetime is controlled by the growth of the snow zone. We find that the dynamo lifetime does not exceed 800 Myr. Thus, our study suggests that a dynamo below the snow zone in Ganymede's core must be a very recent feature."⁷

However, this difficulty does not exist in a biblical timescale of only several thousand years.

Scientists are applying the compositional dynamo concept in Mercury as well, but it works out differently. Mercury is believed to have three layers in its core, but it is thought to follow a more bottom-up change in the core where the solid inner core slowly grows.⁹ Planetary scientists believe a composition gradient in the core would not endure to the present for some objects such as Mars and our moon. Thus, scientists are proposing compositional convection could explain why these objects both have remanent magnetism in rocks but no present magnetic field.

An important question for this model is: would the core of an object such as Ganymede allow for convection, or would it transfer the heat out of the core by normal conduction? If the heat is removed from the core by conduction (without convection), then a dynamo is not possible. There are effects that could prevent fluid convection in Ganymede. One

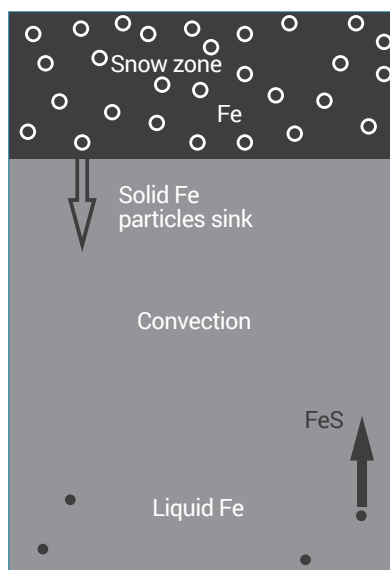


Figure 2. The core of Ganymede is shown as conceived in the top-down iron snow model for Jupiter's moon, Ganymede. Both the black and grey regions make up the core, containing a mixture of iron and iron sulfide. The black region is more solid, while the grey region is more molten, containing more iron sulfide. The black 'snow zone' grows from the top down until it fills the entire core.

difficulty with the iron 'snow' model for Ganymede is whether sinking iron particles in an Fe-FeS fluid could drive convection? There are experimental studies on fluid properties and thermodynamic properties of Fe-FeS mixtures, including some at high pressures. But planetary scientists seem to consider mostly the thermodynamics and heat conduction. The role of sinking iron particles is difficult to include into simulations and calculations. The following quote makes this difficulty clear:

"We are not aware of any study on the convection structure of the ambient liquid induced by settling particles. In an experimental work on another topic by Blanchette and Bush ... it is stated as a side note that particles settle as individuals creating no large-scale convection. Clearly, the question of whether the sedimentation of iron particles generates large-scale convection,

which is necessary for magnetic field generation ... remains an open issue."⁷

Another difficulty is that the composition of planetary cores is actually not well known. Even for Earth's outer core the composition is still debated.^{10,4} The proportion of sulfur is a key factor in studies of Ganymede's core. Scientists have used models with a range of possible proportions of sulfur in Ganymede's core. As the fraction of sulfur is increased, this lowers the melting temperature and allows the iron mixture to stay molten at lower temperatures. So, increasing sulfur can make convection more likely. However, if the fraction of sulfur is increased too much, it can prevent convection.⁸ This is because electrical conductivity decreases with an increasing fraction of sulfur. The lower conductivity raises the temperature and leads to more heat transfer out of the core by conduction, without convection. For some iron 'snow' scenarios, calculations do produce a magnetic field of approximately the right magnitude, but they assume high percentages of sulfur over 23%, which are probably unrealistic.⁸ So, planetary dynamo models still struggle to explain Ganymede possessing its own magnetic field.

A creation view

The magnetic field model of Dr D. Russel Humphreys has been more successful than old-age magnetic dynamo theories. (Other young-age creation models for magnetic fields may be possible but, to date, Humphreys' model is the only one put forward.) Humphreys applied his model to the magnetic fields of Earth, Uranus, Neptune, Mercury, our Sun, and bodies in our solar system.^{11–16} Mercury is slightly smaller than Ganymede but possesses a larger iron core with both solid and liquid layers.^{17,7} Humphreys' model proposed

that when God created the planets he initially made them out of water in the manner described for Earth in Genesis 1 and 2 Peter 3, “out of water”.

This model has significant advantages over the old-age dynamo model. The dynamo model requires a molten conducting core such as liquid iron. It also requires convection motion of the fluid and is very dependent on the size of the core and the rate of rotation of the planet. But in Humphreys’ model, the core need not actually be melted, it just needs to be a conductor. The initial magnetic field from creation decays to the present. This has been described as ‘free decay’ because the field decreases in intensity over thousands of years. Humphreys’ model assumes a young age for the Earth and solar system and leads to realistic values for the magnetic dipole moment for Earth, Mercury, and the other planets. This makes Humphreys’ model more broadly applicable than dynamo theories. Thus, it can be applied to Ganymede as well, as Humphreys has done.¹⁵

In Humphreys’ model for the creation of magnetic fields, the exact composition of the iron core after creation is not known, but this does not create a problem in applying the model. The core’s composition is estimated by interior structure models that attempt to match the overall density of the moon to gravity measurements taken by spacecraft (the *Galileo* mission). Today, Ganymede is believed to have an ice shell of roughly 200 km, then a silicate mantle of about 1,700 km, and this leaves the core as roughly 700–800 km in radius.^{3,18,7} However, these are only rough approximations. If the core is smaller, it needs to have a composition closer to pure iron in order to generate the measured magnetic field. But if the core is larger, then it could have a composition more in a light element such as sulfur (in FeS). In Sohl 2002,¹⁸ an analysis was done of the *Galileo* gravity data for the Galilean moons of Jupiter. They

describe Ganymede’s magnetic field thus:

“Magnetometer measurements of the *Galileo* spacecraft have shown that Ganymede possesses an intrinsic magnetic field with equatorial and polar field strengths at the surface of 750 and 1,200 nT, respectively.”

They go on to give a range of values on the size of the Ganymede core: “The ice shell was suggested to be about 800 km thick. The core may have a radius between 400 and 1,300 km.” All these values are consistent with Humphreys’ model.

Conclusions

At creation, should we assume that the composition of the core was uniform throughout? This is a simplifying assumption but not really a requirement. If there was a composition gradient in the core initially where it was closer to pure iron at the core mantle boundary but possessed more FeS at the bottom of the core, this would be unstable and so sinking iron ‘snow’ and rising FeS would be possible. Such a composition gradient could alter how rapidly the magnetic field decays for some period of time until the core reached a more stable uniform composition. So, to this author it seems the ‘iron snow’ concept is possible, but it would not drive a dynamo in Ganymede, and it would not invalidate Humphreys’ magnetic model. Thus, a young-age creation perspective has real explanatory power for understanding magnetic fields of planets, moons, and other objects in space.

References

1. Spencer, W.R., Ganymede: the surprisingly magnetic moon, *J. Creation* 23(1):8–9, 2009.
2. Gomez-Perez, N. and Wicht, J., Behavior of planetary dynamos under the influence of external magnetic fields: application to Mercury and Ganymede, *Icarus* 209:53–62, 2010.
3. Bland, M.T. *et al.*, The production of Ganymede’s magnetic field, *Icarus* 198:384–399, 2008.
4. Breuer, D. *et al.*, Iron snow, crystal floats, and inner-core growth: modes of core solidification and implications for dynamos in terrestrial planets and moons, *Progress in Earth and Planetary Science* 2, Article no. 39, 16 Nov 2015.
5. Kivelson, M.G. *et al.*, The permanent and inductive magnetic moments of Ganymede, *Icarus* 157:507–522, 2002.
6. Hauck, S.A. *et al.*, Sulfur’s impact on core evolution and magnetic field generation on Ganymede, *J. Geophysical Research* 111:E09008, 2006.
7. Ruckrieman, T. *et al.*, The Fee snow regime in Ganymede’s core: a deep-seated dynamo below a stable snow zone, *J. Geophysical Research: Planets* 120(6):1095–1118, Jun 2015.
8. Littleton, J.A.H. *et al.*, Thermal convection in the core of Ganymede inferred from liquid eutectic Fe-FeS electrical resistivity at high pressures, *Crystals* 11:875, 2021.
9. Takahashi, F., Mercury’s anomalous magnetic field caused by a symmetry-breaking self-regulating dynamo, *Nature Communications* 10:208, 14 Jan 2019.
10. Litasov, K.D. and Shatskiy, A.F., Composition of the Earth’s core: a review, *Russian Geology and Geophysics* 57(1):22–46, 2016.
11. Humphreys, D.R., Reversals of the earth’s magnetic field during the Genesis Flood; in: Walsh, R.E., Brooks, C.L., and Crowell, R.S. (Eds.), *Proceedings of the First International Conference on Creationism*, Creation Science Fellowship, Pittsburgh, PA, 2:113–123, 1986.
12. Humphreys, D.R., The magnetic field of Uranus, *CRSQ* 23:115, 1986.
13. Humphreys, D.R., Good news from Neptune: the Voyager II magnetic measurements, *CRSQ* 27(1):15–17, 1990.
14. Humphreys, D.R., Physical mechanism for reversals of the earth’s magnetic field during the Flood; in: Walsh, R.E. and Brooks, C.L. (Eds.), *Proceedings of the Second International Conference on Creationism*, Creation Science Fellowship, Pittsburgh, PA 2:129–142, 1990.
15. Humphreys, D.R., The creation of cosmic magnetic fields; in: Snelling, A.A. (Ed.), *Proceedings of the Sixth International Conference on Creationism*, Creation Science Fellowship, Pittsburgh, PA, pp. 213–230, 2008.
16. Humphreys, D.R., Mercury’s magnetic field is fading fast—latest spacecraft data confirm evidence for a young solar system, *J. Creation* 26(2):4–6, 2012.
17. Dumberry, M. *et al.*, Mercury’s inner core size and core-crystallization regime, *Icarus* 248:254–268, 2015.
18. Sohl, F. *et al.*, Implications from *Galileo* observations on the interior structure and chemistry of the Galilean satellites, *Icarus* 157:104–119, 2002.