Understanding of the interactions with Ganymede's Magnetic field ⋆

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Accepted XXX. Received YYY; in original form ZZZ

ABSTRACT
While most people would hunt for gold and precious metals, some of us decided to do the opposite: find stars with no metals, while others studied galaxies and also star clusters. We have conducted an analysis... v We have found that... v This means... v We conclude that...

Key words: Science, Astrophysics, PHYS369.

1 INTRODUCTION

Jupiter has the largest magnetosphere in our Solar System, measuring from $100R_j$ (R_j = 71,400km) on the day side to 150-200R_j on the night side. It spans approximately 20 solar diameters wide and encompasses many of the orbiting Jovian moons Gehrels & Matthews (1976). Jupiter's magnetic field is compromised of three sections: the outer region (where the most variation occurs due to being bombarded with the solar wind and interplanetary material), the middle zone, which rotates with the magnetic field and shell of plasma that Jupiter produces, and the inner zone, the densest part of the magnetosphere, which can be found around and close to the surface Rogers (1995). The magnetic field present on Jupiter is generated by electrical currents in the outer core, composed of liquid metallic hydrogen, maintained by the rotational motion of the planet. This induces two magnetic models - open and closed. In a closed case, the magnetic field is induced due to the stress of the centrifugal forces, all happening on trapped low-energy plasma from large and rapid rotation. The open case is produced to make up for centrifugal plasma that radiates outward. This process produces a heliosphere from Jupiter, similar to the solar wind produced by the Sun. This can impose interesting effects on nearby objects, in particular, Ganymede Gehrels & Matthews (1976).

Ganymede is a unique moon, tidally locked to Jupiter, larger than Mercury and Pluto, and the ninth-largest object in the Solar System. It produces its own magnetic field, a characteristic never discovered on a moon, detected by the Galileo spacecraft Gurnett et al. (1996), which exists due to the moon's molten iron core, within Jupiter's magnetosphere Stevenson (2003). Magnetic fields occur due to radioactive decay and heat from the formation of matter, which transpire from collisions and compression of matter. After thousands of years, the core becomes so hot that it reaches the melting point of iron - hence why there is a molten iron core. This core is illustrated in figure 1. For Ganymede, the matter used to form the satellite was (most likely) an accretion of dust and gas from the creation of Jupiter. It was much

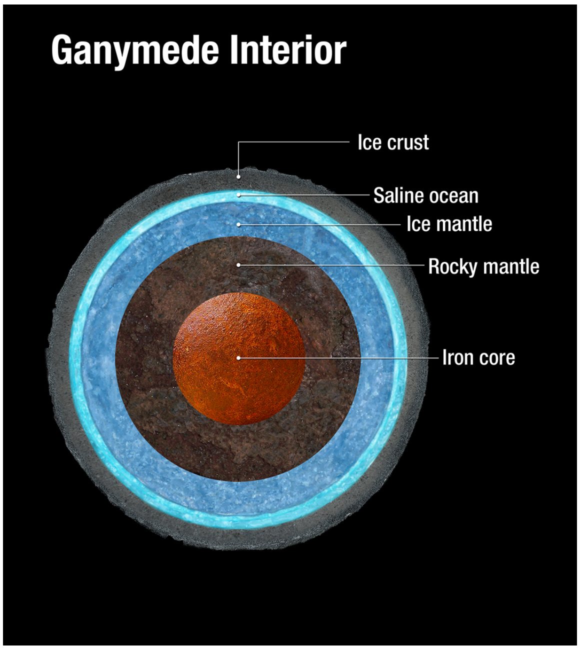

Figure 1. The figure shows the interior make-up of Ganymede, presenting the iron core, rocky mantle, icy mantle, saline underground ocean, and icy crust.

Source: NASA Zell (2015).

⋆ Based on observations obtained with the ZZZ, ZZZ (you can say here what telescopes/data-sets were used).
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quicker at forming than other Jovian moons as it was closer to the planet, where the dust and gas were denser Explorer (2021). Convection within the liquid iron core, influenced by Jupiter's tidal forces, induces the magnetic field.

Closed field lines can be seen at a region 30º below latitude, in which charged particles are trapped, creating a radiation belt - a region surrounding the moon where charged particles accumulate due to the magnetic field - composed of electrons, ions and energetic particles. We can observe and analyze the magnetic field produced by Ganymede and how this field alters the moon's interactions with Jupiter Society (2022). By studying public data retrieved by spacecraft that have flown by Ganymede, such as Voyager 1/2, Galileo, New Horizons, Pioneer 10/11, and Juno, we can examine trends, and explain results present on Ganymede, such as surface weathering.

Weathering can be observed on Ganymede, as the surface is very asymmetric, this is due to Jupiter's magnetosphere plasma being directed along the closed magnetic field lines to Ganymede, bombarding and colliding with the poles. Hence the poles appear to be bright, and the equatorial planes to not be as affected. Ice affected by radiating particles - due to the moon's magnetic field - is why the poles are so bright. Spacecraft such as Pioneer 10 and 11, Voyager 1 and 2, New Horizons, Galileo, and Juno spacecrafts all completed at least one flyby of Ganymede and collected data on the surface features - along with many other features. Ganymede's surface is composed of equal parts of rocky material and water ice and has two types of terrain - dark regions, which are old and full of impact craters, and young, light regions, where the terrain is molded due to tectonic-plate movement from tidal heating - repeated deformation of a body due to gravitational waves of another body - due to the Jovian moon being situated so close to Jupiter Observatory (2023). The light terrain has cross-cutting lanes and a grooved surface. These light and dark terrains are visible through the satellite's thin polar caps.

Dark terrain makes up for around $\frac{1}{3}$ of Ganymede's surface and based on measured crater densities, of which there are many in the dark sections of Ganymede, the terrain is estimated to be over 4 billion years old Bagenal et al. (2007). This is nearly the same age as Jupiter, and as Ganymede is thought to have been created at around the same time as Jupiter, the dark terrain, therefore, holds information for the processes that have affected the moon since it was created.

Light terrain is believed to be tectonic in nature, takes up $\frac{2}{3}$ of Ganymede's surface, and is a result of tidal heating events, because of Jupiter. Tidal heating could have exhausted the lithosphere (the solid, outer part of the moon), causing cracks and deforming the once-dark terrain. High-resolution images, taken from the Galileo spacecraft, prove the existence of the tectonic grooved light terrain Smith et al. (1979). Another cause for the light terrain may be cryovolcanoes - a volcano that erupts with ice, water, and other materials instead of molten rock and ash - erupting water onto the surface.

Ganymede also hosts its own atmosphere, which is oxygen-rich - abundant in O, O_2, and O_3 Explorer (2021). The Jovian moon's atmosphere is theorized to be due to ultraviolet radiation, causing molecules on the icy surface of the moon to split into hydrogen and oxygen, where the oxygen is trapped in the atmosphere and hydrogen is expelled into space Hall et al. (1998). There is an ionosphere - a layer containing a high concentration of ions and free electrons - within the atmosphere. It is believed that the ionosphere on Ganymede is composed of molecular oxygen at the polar regions of the moon, and atomic oxygen ions at low latitudes. Theories suggest the ionosphere should exist, as oxygen molecules are ionized by the impacts of the energetic electrons arising from the magnetosphere, and by ultraviolet rays radiated from the Sun. Protons are absent in all regions of Ganymede's ionosphere Eviatar et al. (2001). The presence of Ganymede's atmosphere causes an effect called 'air glow', where there is a faint emission of light as a result of the interaction between atomic oxygen and energetic particles. Air glow causes bright spots to appear on the polar regions, called polar auroras, and are due to the magnetic field present on Ganymede.

All of the characteristics of Ganymede mentioned above are observable. In this report, we will investigate the magnetic field and the effects of the unusual magnetic field of Ganymede. We will use a magnetic pole simulation between Ganymede and Jupiter (2), focus on how the Jovian moon's magnetic field interacts with Jupiter's magnetic field, by finding available data and plotting graphs as shown in (**??**). Then, we will explore similarities between Ganymede's magnetic field and surface weathering patterns, to find a correlation between the phenomena. Our research will explain why Ganymede looks the way it does, and allow us to gain a deeper understanding of the interactions that take place between Ganymede and Jupiter.

2 SIMULATION

Content:

What the simulation does

Why do we want to create a simulation

The processes and physics used

Diagrams:

The magnetic field of Jupiter and Ganymede

The motion of Ganymede around Jupiter

3 DATA SEARCH

Content:

Data Selection

Coordinate systems

Why we chose the spacecrafts

Diagrams:

Coordinate systems

flyby paths of the spacecraft

As this project is mainly focused on Ganymede's magnetic field, we chose to use the Galileo spacecraft for data, as it recorded measurements of magnetic field strengths and made multiple flybys around Ganymede Vogt et al. (2022). Spacecraft such as Voyager 1 and Voyager 2 studied the surface features of Ganymede, so it would not be useful to consider them for magnetic field research. The magnetic field data recorded by the Galileo spacecraft, alongside data for its position with respect to Jupiter and Ganymede, used within this paper, were retrieved from the *Amda* website CDPP (CDPP).

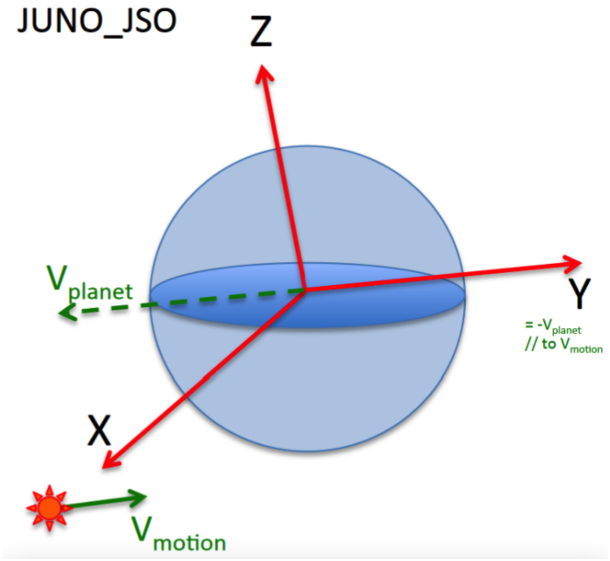

Figure 2. The figure illustrates the Jupiter-Sun-Orbit coordinate system . The X-direction is aligned with the vector from Jupiter to the Sun, the Y-direction is aligned with the Sun's velocity in Jupiter's frame V_{motion}, and the Z-direction is the cross product direction of x and y. The origin of the coordinate system is at the centre of Jupiter.

Source: Bagenal & Wilson (2016)

3.1 JSO Coordinate System

The Jupiter-Sun-Orbit, or JSO, coordinate system, shown in figure 2, is a coordinate system used specifically when taking measurements around Jupiter. The system aligns itself with Jupiter, the Sun, and Jupiter's planetary velocity [Bagenal & Wilson (2016)].

The X-vector is equal to R_{JS}, the unit vector from Jupiter to the Sun. The Y-vector is aligned with the direction of the Sun's velocity in the frame of Jupiter (i.e. the opposite direction of Jupiter's velocity in the Sun's frame). The Z-vector is in the vector product direction of the X and Y vector directions. It is important to note that +Z is no longer ecliptic North due to the direction of V_{motion} Bagenal & Wilson (2016). Jupiter's orbit is tilted by 1.303° to the ecliptic plane and by 6.09° to the Sun's equator, and Jupiter's spin axis is tilted by 3.13° with respect to its orbital plane.

3.2 Phi0 Coordinate System

PhiO is a fixed coordinate system, defined by the co-rotation velocity vector at Ganymede (Phi, ϕ) and the Jovian spin axis (Omega, ω) Kivelson (2022). These vectors are perpendicular to one another. Phi is positive in the direction of co-rotation and Omega is positive northward. Ganymede's ϕ is the X-coordinate whilst ω is the Z-coordinate. The Y-coordinate completes the right-handed set and points towards Jupiter from Ganymede. Basis vectors of the system are fixed at the satellite's closest approach (i.e. epoch time).

4 METHODOLOGY

Content:

Literature research

How data was analyzed

Understanding the program

Changing of dates/times for the spacecraft - why did we choose these days and times

Equations used?

To determine the magnetic field strength on the surface of Ganymede, we opted to use observed data from Galileo's flyby of the satellite on the 27th December 2000 NASA (NASA), as it had more frequent and consistent measurements in comparison to previous flybys and the probe flew near to Ganymede's southern pole. The measurements taken of the magnetic field during the flyby have contributions from both Jupiter and Ganymede. To isolate Ganymede's magnetic field from Jupiter's contribution, multiple Python scripts, available in appendix A, were written to first identify time frames in which Galileo was in approximately the same position as it was during the December 2000 flyby, and then to modify one of these occasions' data to produce artificial Jupiter field data, which could be subtracted to isolate Ganymede's field during the flyby.

4.1 Identifying occasions with a similar Galileo position to December 2000's flyby

The first Python script (Appendix A used an input text file containing position data from *Amda* for Galileo's orbit of Jupiter from the 1st September 1996 to the 1st September 2003. If the position of the spacecraft was within approximately 5 Jupiter radii in each JSO direction of its position during the December 2000 flyby of Ganymede, then that data point was added to an output file. The position of Galileo during the December 2000 flyby was taken as its average across the stated time frame NASA (NASA), measured to be (-15.2, 0.57, 0.84) in JSO coordinates CDPP (CDPP).

The script identified a total of 7 additional occasions where Galileo was within the specified position range: 9th October 1999, 24th November 1999, 2nd January 2000, 21st February 2000, 20th May 2000, 22nd May 2001 and 5th August 2001, each having a duration of between 6.5 and 17.5 hours. The time series of observed magnetic field strength at Galileo for the first six of these occasions are shown in figure 3.

4.2 Isolating Ganymede's magnetic field from December 2000's flyby data

Two new Python scripts were then written to remove Jupiter's contribution from the data. The May 2000 data was determined to have a non-flyby peak of similar magnitude to the December 2000 plot if the flyby spike was ignored, and so the script used May data to construct artificial December 2000 data for Jupiter's contribution only, which could then be subtracted from the December 2000 time series in figure 4 to effectively 'isolate' Ganymede's field. The artificial data was created by calculating the difference between the May and December peaks when there was not a flyby and adjusting the May data by the average distance. The script

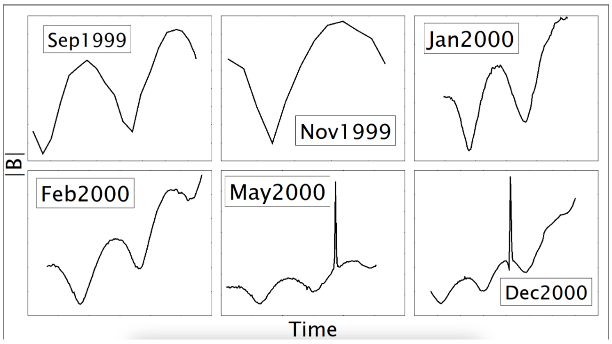

Figure 3. The figure presents six graphs, highlighting the time series of observed magnetic field magnitude by Galileo during six occasions where Galileo's position was similar to that of its December 2000 flyby of Ganymede. Moving across from the top-left: 9$^{\text{th}}$ October 1999, 24$^{\text{th}}$ November 1999, 2$^{\text{nd}}$ January 2000, 21$^{\text{st}}$ February 2000, 20$^{\text{th}}$ May 2000, 27$^{\text{th}}$ December 2000.

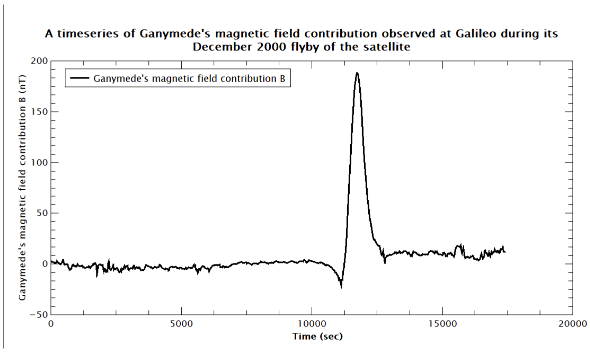

Figure 4. The figure presents a time series of the magnetic field on the 27$^{\text{th}}$ December 2000 flyby of Ganymede, measured by Galileo.

outputted an ASCII data file with values for time, magnetic field contribution, and Galileo-Ganymede distance for the isolated Ganymede data.

Two plots were then produced - a time series of Ganymede's magnetic field contribution and a plot of Ganymede's magnetic field contribution against Galileo-Ganymede distance - for analysis of the field. The distance plot was solely for the Ganymede encounter period, where there was a noticeable contribution from Ganymede and included both the approach and retreat, with a fit of the form $\frac{A}{x^3} + B$ applied where x is Galileo-Ganymede distance and A and B are constants. This particular fit was chosen as magnetic field strength from a dipole has an inverse cube law relationship with distance Michaud (2013), whilst also allowing for a potential base field due to other sources. The fit allowed for extrapolation to estimate the surface field at a distance of 1 Ganymede radius using the determined values of A and B.

4.3 Consideration of Ganymede's magnetic field rotation when compared to expected results

During the December 2000 flyby of Ganymede, Galileo flies close to the geographic north pole of Ganymede Kivelson & Russell (1955). However, the magnetic north pole is rotated by $176 \pm 1^\circ$ with respect to Jupiter's spin axis and $24 \pm 1^\circ$ from the Jupiter-facing meridian plane toward the trailing hemisphere Kivelson et al. (2002). This must be accounted for to adjust the expected value before it can be compared to the surface field estimate we have obtained.

4.4 Analysis of the May 2000 flyby data and estimation of surface magnetic field strength at Ganymede

It can be seen from figure 3 that the May 2000 data also includes a flyby of Ganymede, characterized by the large spike in observed magnetic field strength at Galileo. This flyby specifically occurred on 2000-05-20 NASA (NASA), in a similar position with respect to Jupiter (within 5 Jupiter radii in each JSO coordinate as discussed) as the December 2000 flyby. However, the May flyby crossed near the geographic equator Kivelson & Russell (1955).

The method used for obtaining a surface magnetic field strength at Ganymede for the December flyby was used to also obtain a value for the May flyby. The February 2000 data from approximately the same position with respect to Jupiter was used to create the artificial May data as it was determined to have a non-flyby peak of similar magnitude to the Jupiter field in May. The rotation of Ganymede's magnetic field was then taken into account and compared to the expected value from the literature.

5 RESULTS

Content:
Similarities and differences to the simulation
Data analysis using the program in python
Magnetic interactions with Jupiter - why and how they occur
What conclusions can be found
Diagrams:
Program interactions
Flyby graphs
Magnetic field graphs
interactions with the surface of Ganymede

5.1 Result 1

blah

5.2 Result 2

blah

5.3 Result 3

blah

6 DISCUSSION

Blah blah blah

7 CONCLUSIONS

We have found that:

- a
- b

Content:
General overview
What we originally thought
Summary of what we found
How our thoughts changed
Our understanding of the universe
Limitations
Things we could do next time

A limitation of this project is the lack of data for the flybys of Ganymede. For example, when investigating electron densities of the Jovian moon, only roughly half an hour of data was available to utilize.

ACKNOWLEDGMENTS

The authors are thankful to... .

This work is based in part on data from...

We have benefited immensely from the public available programming language PYTHON, including NUMPY & SCIPY (Van Der Walt et al. 2011; Jones et al. 2001), MATPLOTLIB (Hunter 2007), ASTROPY (Astropy Collaboration et al. 2013) and the TOPCAT analysis program (Taylor 2013). This research has made use of the VizieR catalogue access tool, CDS, Strasbourg, France.

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APPENDIX A: PYTHON SCRIPTS

Python script(s) for identifying occasions with a similar Galileo position to December 2000's flyby: https://github.com/IMAGINE-Lancaster-University/IMAGINE/tree/main/Data%20Python%20Scripts/JSOpositiondata. Python script(s) for constructing artificial magnetic field data and removing Jupiter's magnetic field contribution: https://github.com/IMAGINE-Lancaster-University/IMAGINE/tree/main/Data%20Python%20Scripts/GanymedeIsolation.