Ganymede and Jupiter: An Investigation into the Magnetic Field Interactions Between a Unique Moon and its Host Planet ⋆

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ABSTRACT
The Jovian system has large amounts of magnetic interaction. One of the most unusual arises from its largest moon, Ganymede. Situated 15 Jupiter radii from Jupiter, Ganymede produces a magnetic field. We aimed to investigate the magnetic interactions between Jupiter and Ganymede, using data from the Galileo spacecraft's many flybys. Firstly, we find the magnetic field strength of Ganymede on May 2000, at the equator and the poles. We account for any discrepancies in the magnetic field due to the measurements being taken on the day/night side of the moon. Next, we compared our results to a simulation written in python of the magnetic field of Ganymede at its surface. We then explore electron and ion interactions in Ganymede's magnetic field due to Jupiter's plasma interactions using raw NASA data. We find the magnetic field strength of Ganymede to be 700 ± 20 nT at the equator, 2.67σ away from the expected value of 820 ± 40 nT, and 1670 ± 90 nT at the poles, 2σ away from the expected value of 1400 ± 100 nT (confirmed by our simulations of the magnetic field at the poles). We will also show that there are discrepancies of the magnetic field strength of the surface of Ganymede, due to the day side and night side of the moon. We found magnetic field strengths of 99 ± 1 nT and 110.5 ± 0.9 nT respectively. We also found spikes in electron and ion energies on dates of plasma interactions, producing electron fluxes of 227.5 ± 0.5 cm^{-3} on 06/09/1996, and 13.79 ± 0.5 cm^{-3} on 05/04/1995.

Key words: Science, Astrophysics, PHYS369.

1 INTRODUCTION

Jupiter has the largest magnetosphere in our Solar System. It spans approximately 20 solar diameters (150R_J, where R_J = 71,492km) and encompasses many of the orbiting Jovian moons (Gehrels & Matthews 1976). Jupiter's center to the bow shock of the magnetosphere is approximately 100R_J, and the magnetotail can stretch to a radius of 150R_J. Jupiter's magnetosphere is compromised of three sections: the outer region, 40-90R_J,(where most variation occurs due to being bombarded with the solar wind and interplanetary material), the middle zone 10-40R_J, which rotates with the magnetic field and shell of plasma that Jupiter produces, and the inner zone, 1.2-10 R_J (Gehrels & Matthews 1976), 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 can impose interesting effects on nearby objects, in particular, Ganymede (Gehrels & Matthews 1976).

Ganymede, radius 2,634km, is a unique moon, tidally locked to Jupiter at an orbital distance of around 15R_J. It is larger than Mercury and Pluto and is the ninth-largest object in the Solar System. It produces its own magnetic field, a characteristic never discovered on any other 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). Radioactive decay and compression of matter heat the core. Thousands of years after the formation of Ganymede, 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. Ganymede was most likely formed via the accretion of leftover dust and gas in the circumplanetary disk around Jupiter. Ganymede was formed earlier than other Jovian moons as it was closer to Jupiter, where the dust and gas were denser (Explorer 2021).

⋆ Based on observations obtained with the Galileo spacecraft and using amda and NASA for data.
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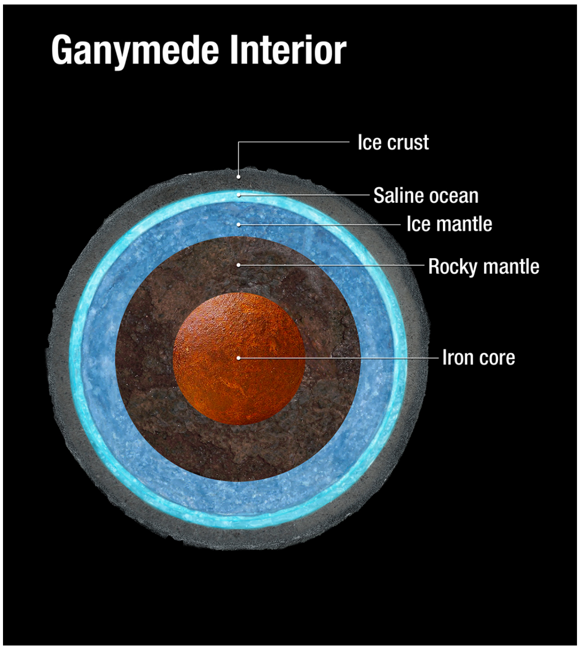


Figure 1. The figure shows the interior make-up of Ganymede, presenting the iron core, rocky mantle, icy mantle, saline underground ocean, and icy crust. Source: NASA (Zell 2015)

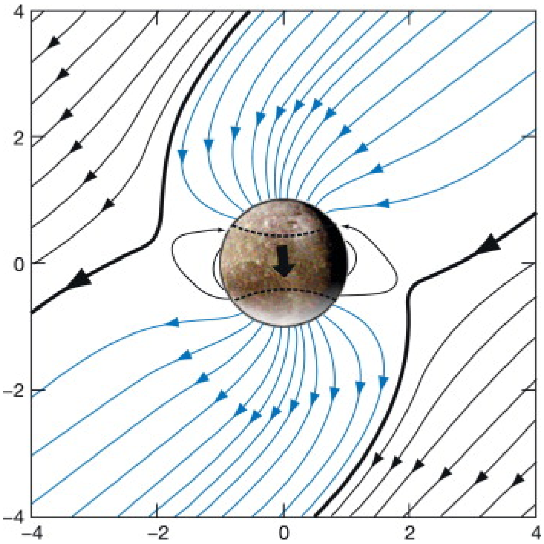


Figure 2. The figure illustrates the magnetic dipole of Ganymede, with the arrows, blue, indicating the direction of Ganymede's field and the black indicate the direction of Jupiter's magnetic field. Source: (Kivelson et al. 2002b)

Convection within Ganymede's liquid iron core, influenced by Jupiter's tidal forces, induces its magnetic field. The diagram in figure 2 illustrates the magnetic field. The poles on the satellite are flipped in comparison to Jupiter's, meaning the direction of the magnetic field lines of Jupiter and Ganymede travel in opposing directions.

Closed field lines can be seen at a region 30º below latitude, in which charged particles are trapped. We can observe and analyze the magnetic field produced by Ganymede and how this field alters the moon's interactions with Jupiter

Figure 3. The figure presents the bright poles on Ganymede. Source: (Explorer 2021)

(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, due to Jupiter's magnetosphere plasma being directed along the magnetic field lines connected to Ganymede, bombarding and colliding with the poles. Hence the poles appear to be bright, while the equatorial planes are not strongly affected. Radiating particles - due to the moon's magnetic field - interact with the ice on the surface of the moon, which is why the poles are so bright (NASA 2022a). This can be seen in figure 3. 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 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 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 ions at the polar regions of the moon, and atomic oxygen ions at low latitudes (Explorer 2021). 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 (excitation and deexcitation) between atomic oxygen and energetic particles. Bright spots appear on the polar regions, called polar auroras, which are due to charged particles impacting along the magnetic field lines on Ganymede.

In this report, we will investigate the magnetic field of Ganymede and its effect on the surface of the moon. We will use a magnetic pole simulation between Ganymede and Jupiter, and focus on how Ganymede's magnetic field interacts with Jupiter's magnetic field, by analyzing how the magnetic field measurements vary between different flybys. 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 DATA SEARCH

2.1 Spacecraft

As this project is mainly focused on Ganymede's magnetic field, we chose to use the Galileo and Juno spacecraft for data, as they recorded measurements of magnetic field strengths and made multiple flybys around Ganymede (Vogt et al. 2022). The probes recorded the magnetic field strength of the day and night side of the Jovian moon (the side facing and not facing the Sun respectively), and at different positions along Ganymede's orbit of Jupiter, allowing us to recognize what effects the Sun and Jupiter have on the satellite's magnetic field. The magnetic field strength and position data recorded by both spacecraft used within this paper, were retrieved from the *Amda* website (CDPP 2022).

2.2 Charged Particle Interactions

A subsection within the magnetic field research of Ganymede is the charged particle interactions, induced by the magnetic field. Ions and electrons cause these interactions, and data regarding these particles can only be observed from Ganymede flybys. We decided to use this section in our report, as to understand the interactions between Ganymede and Jupiter, we need to investigate the changes in electron densities. The Galileo spacecraft was the only spacecraft that had the necessary data, and due to the nature of its flybys, there was a limited amount of data to use - there were only certain dates and times that the probe flew past Ganymede. The following dates and times were used: 06/09/1996 18:00:25-19:44:00, 05/04/1997 6:34:08-7:47:53, 07/05/1997 15:05:07-16:30:43, 20/05/2000 9:35:42-10:41:06.

Using the Energetic Particle Detector (EPD) (), with data from Amda, we found the counts and flux for high-energy electrons in the induced interactions. There were three types of ions and electron classes. For electrons, there is E[0-3], containing electrons that have energies of the range 15 to 93 keV, and F[0-3], with electrons of energies of 93 to 884 keV. Each electron type will exhibit a different number of counts for different energies, as well as a different flux. For ions, there is A[0-8], which describes all of the ions present, and is a combination of two different ion classifications. A[0-7] which are ions with M $\geq$ 1, where M is the atomic number, charge $\geq$ 1 and energies of the range 22-32000 keV; and A[8] which are ions with M $\geq$ 4, charge $\geq$ 2 and energies of 34000-82000 keV.

In order to find the right electron and ion interactions, we needed to narrow down if the spikes in energy were due to Ganymede or if they were interactions with the magnetic field of Jupiter. To do so, we looked into the interactions with the Plasma Science Instrument (PLS). The data provided by PLS is in the form of already generated data graphs, showing the counts in energy changes of the particles and the energy over the area found each day of Galileo's mission. A period of 3 days was taken - the day before, during, and after the high energy electrons and ions were found, in order to gain a range of when interactions of the plasma sheet might have occurred.

On 20/05/2000 and 07/05/1997, there were no interactions near or before the dates, and hence it can be concluded that no interactions with the plasma sheet took place. These dates were taken out of the full analysis of the interactions.

2.3 Electron Densities

The data used for the electron densities were provided from Galileo flybys of Ganymede. To understand the interaction between Ganymede and Jupiter we need to investigate electron densities on the dates stated above, at a distance close to Ganymede. The data used was available on the Planetary Data System on NASA's website (NASA 2022a). In order to plot the electron density data at different radii, we selected the plasma wave subsystem (PWS) electron plasma data so that we could appropriately plot electron density against the distance from Ganymede, measured in Jupiter Radii (R_{J}), $1R_{\mathrm{J}}$ = 71,492km. We had to bear in mind that Ganymede is around 15 R_{J} away, and that we want to be analyzing electron densities at around that distance from Jupiter.

When plotting, there was some variation in quality. The date of 20/05/2000: 9:35:42 to 10:41:06 had large inconsistencies, and as a result was discounted as a date that can be fully analyzed.

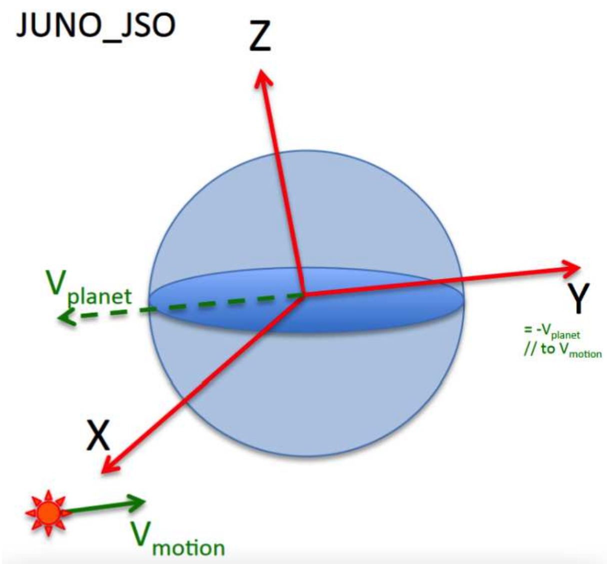


Figure 4. The figure illustrates the Jupiter-Sun-Orbit coordinate system . The x-direction is aligned with the vector from Jupiter to the Sun, the y-direction is aligned with the Sun's velocity in Jupiter's frame V_{motion}, and the z-direction is the cross product direction of x and y. The origin of the coordinate system is at the center of Jupiter ((Bagenal & Wilson 2016)).

2.4 JSO Coordinate System

The Jupiter-Sun-Orbit, or JSO, coordinate system, shown in figure 4, is 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.

2.5 GPhiO Coordinate System

GPhiO is a fixed coordinate system, defined by the co-rotation velocity vector at Ganymede (Phi, ϕ) and the Jovian spin axis (Omega, Ω) (NASA 2022b). 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 (NASA 2022b).

A visualization of the coordinate system with respect to Jupiter can be seen in figure 5. The x coordinate is in the direction of Ganymede's plasma co-rotation direction, the y coordinate is in the direction of Jupiter from Ganymede, and the z coordinate is the spin axis, completing the right-handed set (Kivelson & Russell 1955).

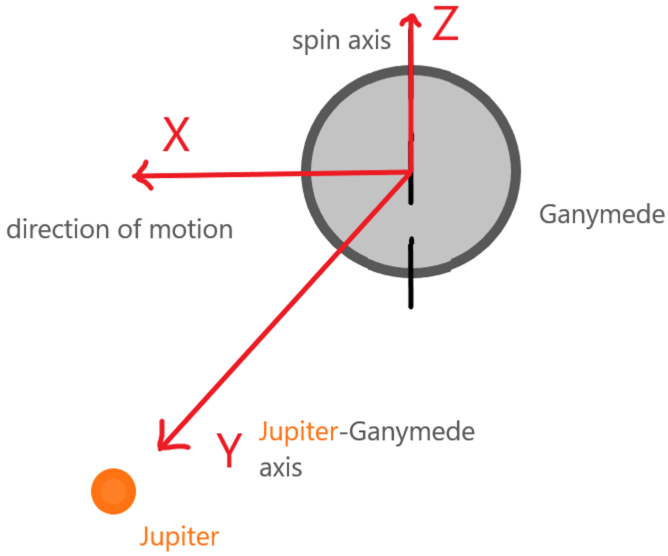


Figure 5. A diagram illustrating the GPhiO coordinate system. It shows that x is in the direction of Ganymede's motion, y is in the Ganymede-Jupiter axis, and z is Ganymede's spin axis.

2.6 Magnetic Field

We used Galileo trajectory information in JSO coordinates to find times when Galileo crossed the noon-midnight meridian at radial distances close to the orbital distance of Ganymede ($15R_J$). We then extracted the magnetic field magnitude at these times to compare the 'background' magnetic field conditions that Ganymede would encounter. Initially, the z-coordinates were considered, but due to the differences in rotational, orbital, and magnetic field axes, accounting for this did not make sense. JSO 2.4 coordinates use the spin axis of Jupiter as the z-axis, 3.13○, and the magnetic field is 10○ offset from this, meaning that the z-axis will always increase as the rotation axis and orbital axis are different. Therefore, the z value would not change the results. As seen below, the z-axis is an extension of the orbital y-axis, while Galileo orbited around the rotation axis. Meaning it will have an ever-increasing z-coordinate. (Appendix A).

There are both positive and negative x values, where the positive values indicate when the satellite was facing the Sun and the negative was facing away from the Sun. To be closely aligned to the x-axis, we want y-values that tend to 0. The main region of interest is 10-20 Jupiter Radii, R_J, due to Ganymede's location of $15R_J$. This range enables us to investigate the entirety of Ganymede's magnetosphere. In addition, it allows us to see the interactions between the dipole on Ganymede and the rotational forces of Jupiter.

2.7 Magnetic Field Models

As we move away from Jupiter, shown in figure 7, it can be observed how the higher-order components of the magnetic field start to disappear. The magnetic field starts to approximate a dipole.

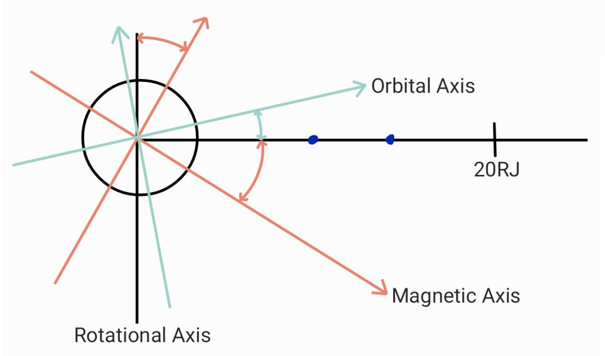


Figure 6. The figure presents the offset of Ganymede's magnetic field and the orbital axis.

Ganymede's magnetic field portrays the behavior of a dipole, figure 8, much more than Jupiter does. This is clear as even at low $r/r_{surface}$, the blue and red areas - north and south pole - are in the middle of the top and bottom of the surface. Note that Ganymede's magnetic dipole is flipped in comparison to Jupiter's - this means that Ganymede's north pole is on the bottom of the moon, and the south pole is on the top. This causes a magnetic moment that travels opposite to Jupiter's.

3 METHODOLOGY AND RESULTS

3.1 Ganymede's Surface Magnetic Field Strength

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 28/12/2000, G29 (NASA 2022a), 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 B, were written to first identify time frames in which Galileo was in approximately the same position as it was during the G29 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.

3.1.1 Identifying occasions with a similar Galileo position to the G29 flyby

The first Python script (Appendix B) used an input text file containing position data from *Amda* for Galileo's orbit of Jupiter from 01/09/1996-01/09/2003. If the position of the spacecraft was within approximately 5 Jupiter radii in each JSO direction of its position during the G29 flyby of Ganymede, then that data point was added to an output file. The position of Galileo during this flyby was taken as its average across the stated time frame (NASA 2022a), measured to be (-15.2, 0.57, 0.84) in JSO coordinates (CDPP 2022).

The script identified a total of 7 additional occasions where Galileo was within the specified position range, making a flyby of Ganymede: 09/10/1999, 24/11/1999, 02/01/2000, 21/02/2000, 20/05/2000, 22/05/2001 and 05/08/2001, 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 9.

3.1.2 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 G29 data for Jupiter's contribution only, which could then be subtracted from the December 2000 time series in figure 10 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 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.

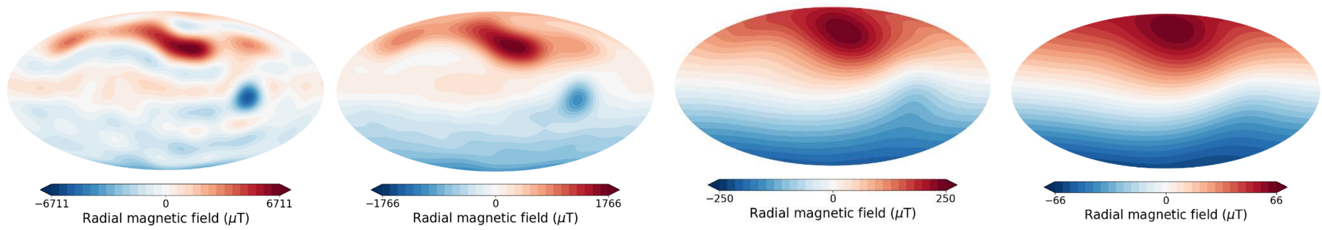
3.1.3 Consideration of Ganymede's magnetic field rotation when compared to expected results

During the G29 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. 2002a). This must be accounted for to adjust the expected value before it can be compared to the surface field estimate we have obtained.

3.1.4 Removal of Jupiter's magnetic field contribution

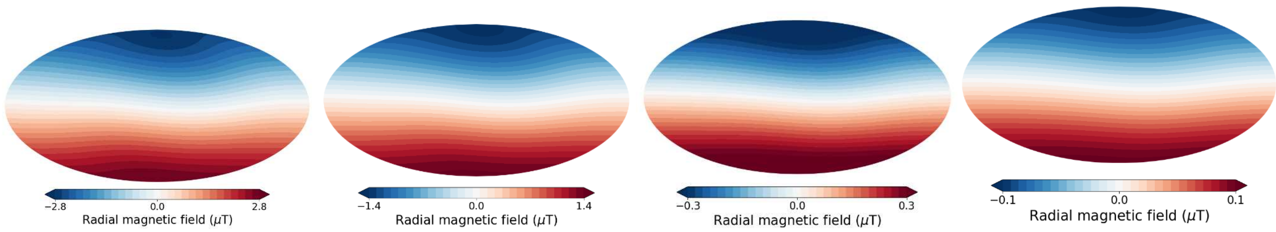
Data from February 2000 and May 2000 were used to construct artificial Jupiter contribution data for the G28 and G29 flybys respectively. The removal of this contribution from the time series in figure 9 produced the plots of Ganymede's isolated magnetic field contribution shown in figures 11 and 12 for G28 and G29 respectively.

It can be seen that in both the plots in figures 11 and



(a) $0.8R_J$ (b) $1R_J$ (c) $1.6R_J$ (d) $2.4R_J$

Figure 7. A model of Jupiter's magnetic field (μT) at $0.8R_J$, $1R_J$, $1.6R_J$ and $2.4R_J$, using data from Juno and Galileo flybys. The red color emphasizes the north pole, where the magnetic field lines begin, and the blue color represents the south pole, where the magnetic field lines end. Where the color is darker, the magnetic field is stronger.



(a) $0.8R_g$ (b) $1R_g$ (c) $1.6R_g$ (d) $2.4R_g$

Figure 8. Model of Ganymede's magnetic field (μT) at $0.8R_g$, $1R_g$, $1.6R_g$ and $2.4R_g$, using data from Juno and Galileo flybys. The red color emphasizes the north pole, where the magnetic field lines begin, and the blue color represents the south pole, where the magnetic field lines end. Where the color is darker, the magnetic field is stronger.

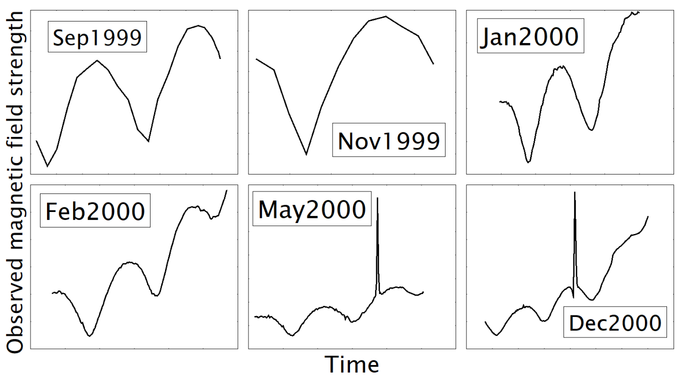


Figure 9. The figure presents six graphs, highlighting the time series of observed magnetic field magnitude by Galileo on six occasions, where Galileo's position was similar to that of the G29 flyby of Ganymede. Moving across from the top-left: 09/10/1999, 24/11/1999, 02/01/2000, 21/02/2000, 20/05/2000, 28/12/2000.

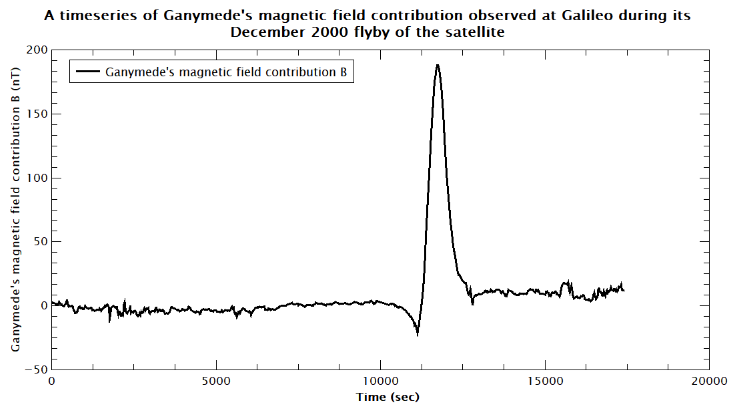


Figure 10. The figure presents a time series of the magnetic field on the 28/12/2000 flyby of Ganymede, measured by Galileo.

12, the magnetic field contribution due to Ganymede observed at Galileo is negligible for Galileo-Ganymede distances greater than approximately 4 Ganymede radii. However, as Galileo approaches Ganymede, there is a significant spike in Ganymede's isolated observed magnetic field contribution, suggesting that Ganymede does indeed have its own magnetosphere.

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

It can be noted from figure 9 that the May 2000 data also includes a flyby of Ganymede, characterized by the large spike in observed magnetic field strength from Galileo. This flyby occurred on 20/05/2000 (NASA 2022a), 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

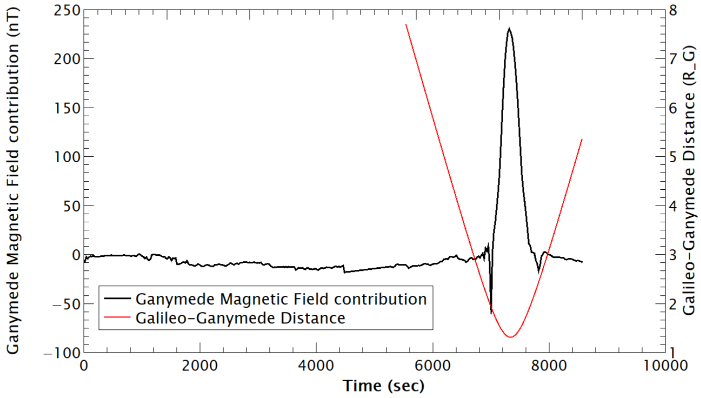


Figure 11. A time series of Ganymede's isolated magnetic field (measured in nT) observed by Galileo during its May 2000, G28, flyby of the satellite, with artificial Jupiter magnetic field data removed from the overall magnetometer reading at Galileo, alongside available data for Galileo-Ganymede distance (measured in Ganymede radii).

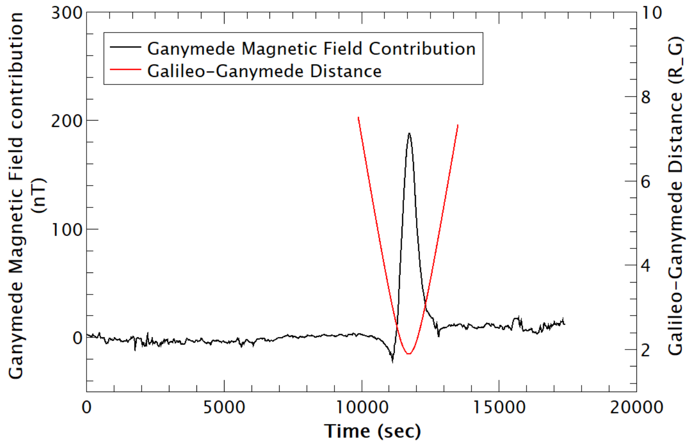


Figure 12. A time series of Ganymede's isolated magnetic field (measured in nT) observed by Galileo during its December 2000, G29, flyby of the satellite, with artificial Jupiter magnetic field data removed from the overall magnetometer reading at Galileo, alongside available data for Galileo-Ganymede distance (measured in Ganymede radii).

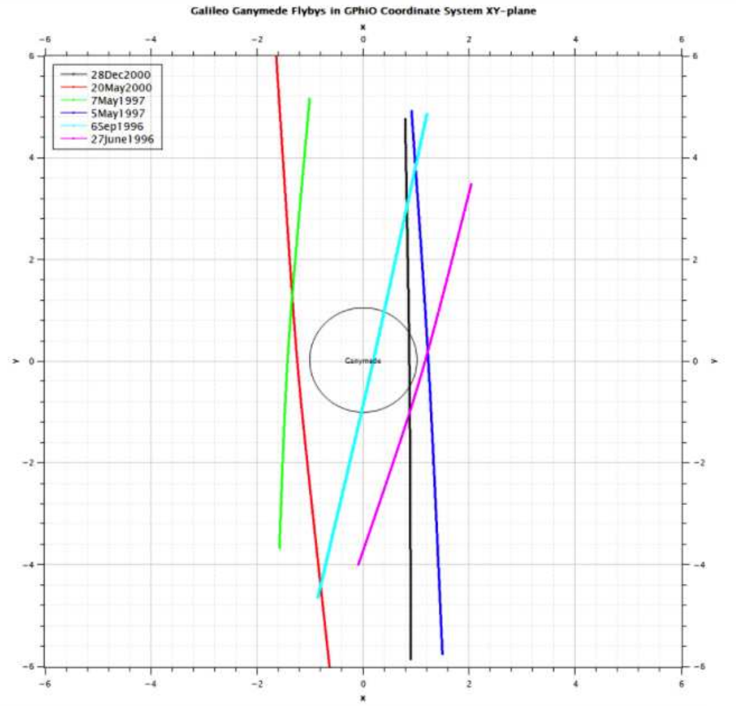


Figure 13. The figure illustrates six Ganymede flybys that the Galileo probe conducted from 1996-2000, it is in the Ganymede-centred phi-omega coordinates (2.5), x-y plane, with Ganymede at the center and the scaling in Ganymede radii. The September 6th, 1996 flyby is the closest to being directly above the pole of Ganymede at about 0.2 Ganymede radii away, which explains the strong magnetic field data from graph **??**. The other flybys shown previously are at a further distance away from the pole with April 5th, 1997 at 1.6 radii and December 28th, 2000 at 0.85 Ganymede radii. Note that all these flybys occur at different z values, meaning their actual flyby distances are different than the distance from the pole.

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.

Figure 9 shows that the May 2000 and December 2000 plots were at a far greater resolution than the others, particularly in comparison to the 1999 plots. They were both of a similar position to each other (NASA 2022a). Conveniently, the December flyby flew close to the geographic north pole of Ganymede whilst the May flyby flew nearby the geographic equator, as seen in figure 13 and 14, allowing for the observation of both equatorial and polar magnetic field strength behavior from similar positions.

Data from the September flyby shows the closest pass the Galileo probe made of Ganymede, at around 1.15 Ganymede radii, 2900km from the surface, where the field strength reached 1.2 μT. Galileo traveled close to Ganymede's poles, where the magnetic field lines are situated close together, which is noticeable in the red, B_z peak. The peak accounts for most of the magnetic field strength. At first, until 18:50, the magnetic field strength measured is from Jupiter. Then, at 18:50, Ganymede's smaller, but significant, magnetic field strength is measured. B_x and B_y lines switch from negative to positive. After $\approx$ 20 minutes from Ganymede's field being measured, the measurements change back to Jupiter's magnetic field.

Data from the April flyby, as the flyby approached the Jovian moon up to 2.16 Ganymede radii, showed its magnetic field readings are not as strong as the September 1996 flyby. It flew by at a latitude of 56° which, compared to the September 1996 latitude of 80°, meant the probe would not be close to the magnetic pole, hence the magnetic field lines are further apart. The magnetic field peaks at $\approx$ 220 nT where it is the strongest in the x and z directions.

From figure 15, we can see a clear change in the magnetic field strength readings. At 8:17 UT, as the probe approaches Ganymede, the readings change from Jupiter's magnetic field to Ganymede's, over $\approx$ a 30-minute period.

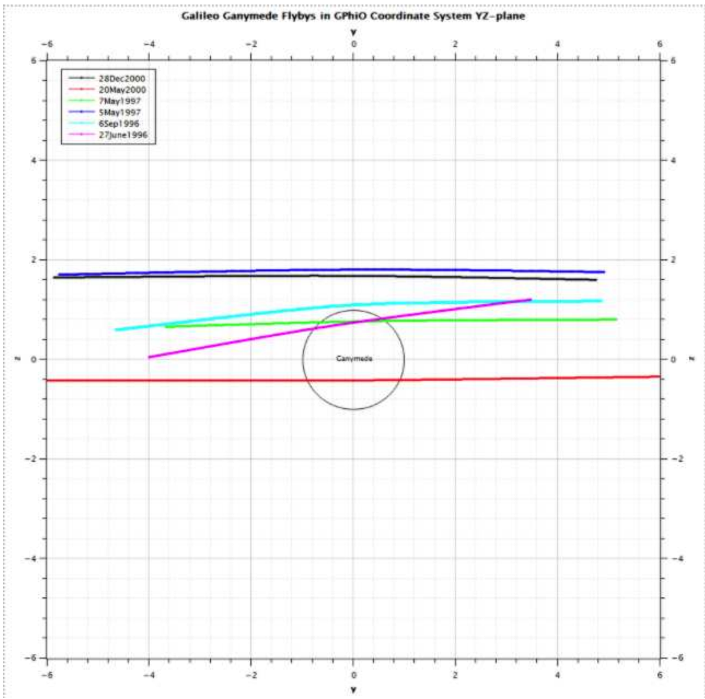


Figure 14. The figure illustrates six Ganymede flybys that the Galileo probe conducted from 1996-2000, it is in the Ganymede-centred phi-omega coordinates (2.5), y-z plane, with Ganymede at the center and the scaling in Ganymede radii.

The peak of the flyby, $\approx$ 300 nT, occurs at 8:25 UT, where the probe is the closest to the magnetic poles of Ganymede, and the probe is at latitude 65° and 2.04 Ganymede radii from the center of the moon.

Having taken plots of some of the Galileo Ganymede flybys, they mostly appear to be fairly similar where the magnetic field amplitudes will peak as the probe gets the closest to Ganymede in the ranges of 1-2 Ganymede radii where one Ganymede radius is 2,631 km. The strongest and closest flyby is the 6th September 1996 where it gets closest at around 1.15 radii, 2900 km from the surface, where the field strength reached 1.2 μT.

3.1.6 Jupiter's day and night side magnetic field strengths

We are investigating the difference in the day and night side of Jupiter's magnetic field strength. The day side field is compressed by the solar wind, whereas on the night side, there is no compression, and the field is stretched outwards. If there is a noticeable effect, of Jupiter's magnetic field strength, we will have to take this into account when removing Jupiter's magnetic field from our Ganymede data.

Initially, we plotted the x and y coordinates of Galileo over the time of the mission, looking for points at which the y-axis is close to 0 and noting the sign of the x-axis. After estimating the x-axis values for all points at which y was close to 0, we were able to look for any similarity between the positive and negative x-axis values. This method only yielded two dates for comparison, 15/10/01 and 14/09/99.

More data was needed to allow for a proper comparison, so we ran it through a python script to filter the data for a range of y, -2-2 Jupiter radii. This gave 13,532 data points, although, for a number of these, there were no magnitudes of the magnetic field strength. After removing all points without a magnetic field strength, 6273 data points were left, split between 1751 for the day side (positive x) and 4522 for the night side (negative x). Limiting the data set to +35 and -35 $R_{\rm J}$ will help reduce any differences. This left 855 data points for the night side.

We plotted graphs and analysed data from the two dates we found earlier - 15/10/01 and 14/09/99. For the day side, Galileo was at 7.46$R_{\rm J}$, providing a magnetic field strength of 880.85 nT. For the night side, Galileo was at -7.46$R_{\rm J}$, providing a magnetic field strength of 907.75 nT. These findings disagree with the expected results, although there is a difference in the y coordinates - 0.34$R_{\rm J}$ for the day side and 0.018$R_{\rm J}$ for the night side. This difference could be the cause of the disagreement with expectations, as the closer the satellite is to the x-axis, meaning a lower y-value, the more aligned it will be with the true day side and night side. These points are where the greatest effects of solar wind compression would be present.

Initially, to analyse the data for both day side and night side magnetic field strength, they were fitted using an exponential relationship. Then using the equations created from these fits, estimations for the magnetic field at 15$R_{\rm J}$ could be created. For the day side data, at a radius of 15$R_{\rm J}$, the magnetic field strength was estimated to be 80 $/pm$ 1 nT. For the night side data, at a radius of -15$R_{\rm J}$, the magnetic field strength was estimated to be 59 $\pm$ 1 nT. These values agree more with the theory but have a flaw in that magnetic fields should not follow an exponential pattern. Instead, it follows the relationship of R^{-3}, therefore these results could not be deemed too accurate. Using this relationship, $y_0 + \frac{a}{x^3}$, gave results of 99 $\pm$ 1 nT for the day side as shown in figure 16, and 110.9 $\pm$ 0.9 nT for the night side.

Contrary to what is expected, the night side has a slightly higher magnetic field strength than the day side. Although there are a number of possible explanations. For the night side, there are fewer data points and a significant gap between -9 and -12 Jupiter radii. Also, it features data points from a Ganymede flyby, this is the spike at -15$R_{\rm J}$. All of these factors could contribute to a less accurate result. Also, the cyclic nature of the magnetic field means there is a greater range of possible values depending on the location of the magnetic field at the time of recording. Finally, the Ganymede flyby data was removed and the night side data recalculated, this is shown in figure 17, and gave a final result of 110.5 $\pm$ 0.9 nT. Therefore even after removing the Ganymede flyby data, there is still a discrepancy. Meaning it most likely stems from the lack of data points, which visually can be seen to have a line slightly higher than expected.

Final results show that the night side has a greater magnetic field, which contradicts our initial understanding as the compression of the field on the day side would cause the magnetic field strength to be stronger than the night side. Therefore, there is no difference at the distance of Ganymede, from the Sun, to consider at this level of research. 15$R_{\rm J}$ is close enough to Jupiter for the effects of solar wind to be unnoticeable.

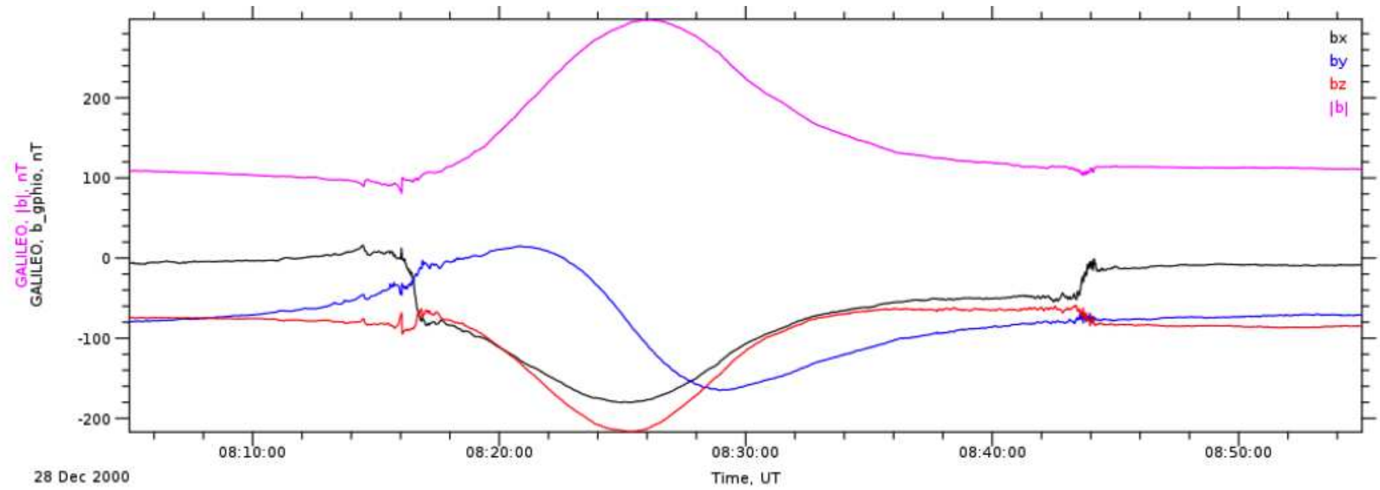


Figure 15. The figure illustrates B_x - black, B_y - blue and B_z - red magnetic field vector components, with values from a flyby of Ganymede on December 28th, 2000 from the Galileo probe in Ganymede-centred phi-omega coordinates (nT).

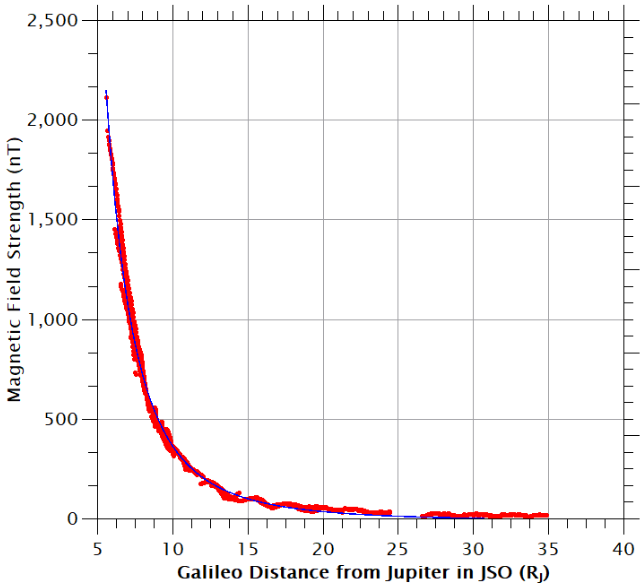


Figure 16. Plot of magnetic field strength on the day side of Jupiter, fitted with the R^{-3} line, shown in blue. Resulting in a magnetic field strength of 99 ± 1nT at $15R_{\rm J}$.

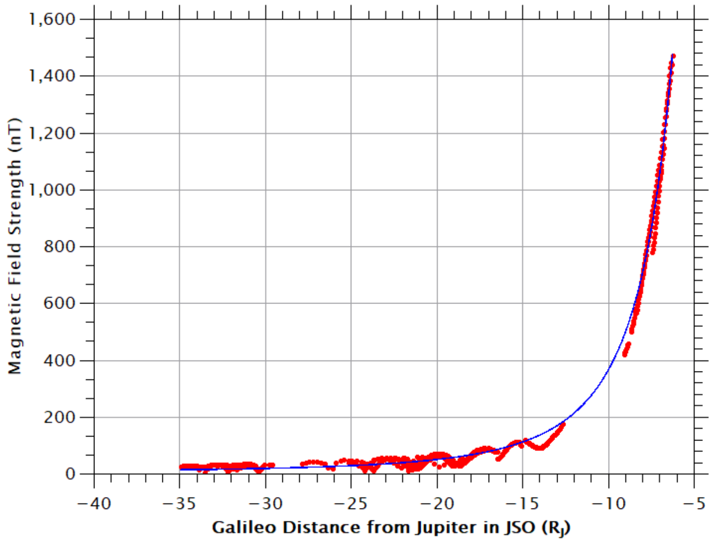


Figure 17. Plot of magnetic field strength on the night side of Jupiter, fitted with the R^{-3} line, shown in blue. Resulting in magnetic field strength of 110.5 ± 0.9nT at $-15R_{\rm J}$.

3.1.7 Analysis at the Equator

A plot was then produced of Ganymede's observed magnetic field contribution against Galileo-Ganymede distance for the May 2000 Ganymede flyby during the magnetic field spike, shown in figure 18. The applied fit represents the data well. The fit parameters in figure 18 were used to extrapolate and estimate the magnetic field of Ganymede at its surface (i.e. 1 Ganymede radius). The surface magnetic field strength, at the equator, was calculated to be 700 ± 20 nT, at $1R_G$.

Whilst it is evident from figure 13 and figure 14 that the May flyby's closest approach was near to the equatorial plane, Galileo's latitude with respect to Ganymede was not exactly 0°, and Ganymede's magnetic field is rotated by 176°, as previously discussed. Therefore, the value from the literature of surface magnetic field strength at the equator of 719 nT must be modified to be suitable for Galileo's magnetic co-latitude during the May 2000 flyby, using equation 1 to calculate the expected magnetic field strength where B is magnetic field strength, M is the dipole magnetic moment ($719\,nT/R_G^3$ for Ganymede (Kivelson et al. 2002a)), r is the distance from Ganymede (1 Ganymede radius at the surface) and θ is the magnetic co-latitude (Kivelson & Russell 1955).

$$B = Mr^{-3}(1 + 3\cos(\theta)^2)^{\frac{1}{2}} \tag{1}$$

Figure 13 and 14, shows that at the closest approach during the May 2000 flyby, Galileo GPhiO coordinates are $(-1.2 \pm 0.2,\ 0,\ -0.4 \pm 0.1)$ with units of Ganymede radii R_G, where estimated uncertainties arise due to human error in reading from the plots. These coordinates indicate

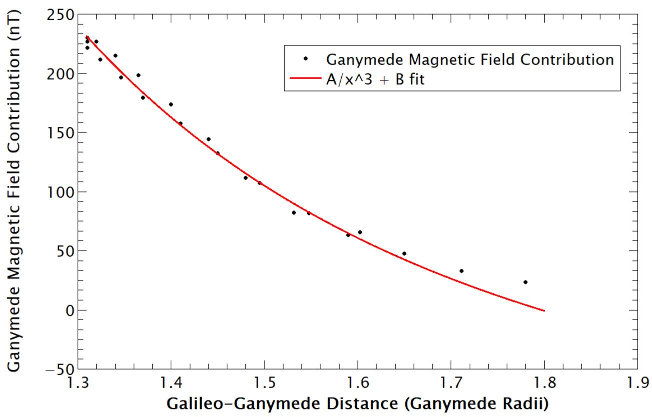


Figure 18. A plot of Ganymede's isolated magnetic field contribution observed at Galileo (measured in nT) against its distance from the spacecraft (measured in Ganymede radii) for its May 2000 flyby of the moon. A fit has been applied with the equation $\frac{A}{x^3} + B$, with determined parameters $A = 850 \pm 20\, nT\, R_G^3$ and $B = -146 \pm 8nT$.

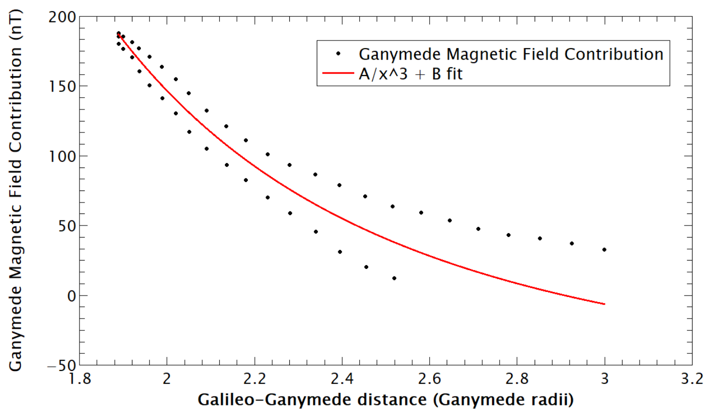


Figure 19. A plot of Ganymede's isolated magnetic field contribution observed at Galileo (measured in nT) against its distance from the spacecraft (measured in Ganymede radii) for its December 2000 flyby of the moon. A fit has been applied with the equation $\frac{A}{x^3} + B$, with determined parameters $A = 1740 \pm 90\, nT\, R_G^3$ and $B = -71 \pm 11\, nT$.

that during the flyby, Galileo flew to the south of the Geographical equator, and was trailing Ganymede's direction of motion. Equation 2 was then used to calculate the geographic co-latitude of Galileo with respect to Ganymede to be $\theta_{geo} = -71.57^\circ \pm 0.02^\circ$.

$$|\theta| = 90^\circ - \arctan \frac{Z}{X} \tag{2}$$

The $176^\circ \pm 1^\circ$, rotation of Ganymede's magnetic field with respect to the spin axis would place the magnetic north and south poles of Ganymede at an offset of $\theta_{offset} = 4^\circ \pm 1^\circ$ from the south and north geographic poles respectively. Therefore, equation 3 can be used to calculate Galileo's magnetic co-latitude θ_{mag} (that is, its co-latitude with respect to the magnetic field orientation) by taking the resultant of both angles.

$$|\theta_{mag}| = \sqrt{|\theta_{geo}|^2 + |\theta_{offset}|^2} \tag{3}$$

The magnetic co-latitude of Galileo's closest approach to Ganymede, with propagated error, was calculated as $72^\circ \pm 18^\circ$. The co-latitude is positive as whilst the flyby was south of the geographic equator, the 176°, rotation of the magnetic field resulted in Galileo being in the magnetic north. This value was then used in equation 1 to estimate the expected surface magnetic field strength contribution from Ganymede at Galileo's magnetic co-latitude as 820 ± 40 nT. Using combined error σ, our obtained result of 700 ± 20 nT is therefore 2.67σ away from the expected value, suggesting that there is some evidence that the two values are different, but further research should be done to investigate whether this difference is real.

3.1.8 Analysis at the Pole

A plot of Ganymede's magnetic field strength against Galileo-Ganymede distance was then produced for the December 2000 flyby data, shown in figure 19, showing very similar behavior to the May 2000 flyby data.

Using the parameters of the applied fit, which appear to represent the data well, it was estimated that the magnetic field of Ganymede at the surface was 1670 ± 90 nT. The December 2000 flyby flew over the geographic north pole of the moon, trailing its motion, with closest-approach GPhiO coordinates of (0.9 ± 0.2, 0, 1.7 ± 0.2) R_G (Kivelson & Russell 1955) so we would expect a greater magnetic field contribution to that at the equator. These flight paths are shown in figures 13 and 14.

Recorded Galileo-Ganymede latitude data was available for the December flyby which placed the spacecraft's closest approach at geographic co-latitude of $\theta_{geo} = 28^\circ \pm 2^\circ$ (CDPP 2022), with error arising due to uncertainty in the human reading from the time series. This was then combined with the discussed magnetic field rotation θ_{offset} in equation 3 to give a magnetic co-latitude of $28^\circ \pm 7^\circ$, corresponding to an expected surface magnetic field strength of 1400 ± 100 nT from equation 1. Therefore, our result of 1670nT is 2σ away from the expected value, where σ is a combined error, and there is some evidence to suggest a difference in the two values. As with the near-equatorial value obtained from the May 2000 flyby data, further research must be done to conclude which value is correct.

3.2 Charged Particle Interactions

The method for investigating the electron and ions in the magnetic field of Ganymede consists of plotting and searching through data, in order to find the right dates, at the right times and observe any interactions.

Using Amda, we were able to pinpoint some areas of high-energy electrons and ions. Data on the graphs provided was sparse, but by analyzing the few points we had, we were able to pick out the main dates that charged particle interactions occurred.

Electron densities were plotted using QTIPlot and analyzed using the built-in data tool to obtain the peaks of electron densities at distances close to Ganymede, $15R_J$, at the specific dates previously mentioned. Then, we used this data to observe any discrepancies or changes through the different dates.

For plasma interactions, we took the date before, during, and after the date the interaction occurred, and noted if there were a high volume of interactions on, after, or before the day of the interaction. If not, the date is disregarded as an interaction with Jupiter's plasma field.

3.2.1 06/09/1996

On 06/09/1996, presented in figure 20, a large number of interactions occurred around Ganymede. There is a peak around the $15R_{\rm J}$ mark, which is the distance that Ganymede is situated from Jupiter. In figure 21 there is some form of "drop off" where no electrons can be seen. There may be a few reasons for this. One reason could be that the electrons cannot be detected, as they have energies that exceed 884 keV. This could be because there are electrons present due to the peak in 22, which would result in no data being found at this electron range but still a flux of electrons in that area. Another reason could be due to cold energy electrons, where the electrons have very low effective temperatures and therefore do not have large amounts of energy in the magnetosphere. This is more unlikely as Ganymede is going through Jupiter's plasma field, and interacting with it, which would cause electrons to become excited to higher energies. An interesting phenomenon is that in the plasma field data, found through the PLS instrument on Galileo, we can observe interactions, where at the time we find high energy electrons and ions. This can be proven by recognizing the number of counts on PLS figure 20b, as at around 18:00 the count rate increases drastically for a very small amount of time. This is presented by the color change from light green, indicating 10^1 to 10^2 counts per second, to some areas converting to yellow/orange, hinting there are 10^4 counts per second. This could be an indication that there are plasma interactions around Ganymede. Comparing to the high energy electrons and ions found in a graph 21a, 21b and 21c, we notice a large amount of lower energy ions and an increase in flux - indicating plasma interactions are causing ions to interact with Ganymede's magnetosphere and expel high-energy particles. This sudden effect of flux may be the cause of the gaping and "dips" seen at around 18:57 on all graphs in figure 21. A possible explanation for this, is the electrons are interacting with the plasma so much, that they are gaining higher energies.

When looking at the electron energies we need to compare to the electron densities at the time of the fly-by. We can see in graph 22 that there is a peak to the electron density. This peak can be found around 15.0 ± 0.5 $R_{\rm J}$, which is the distance of Ganymede from Jupiter in Jupiter Radii, giving an electron density of 227.5 ± 0.5 cm^{-3}.

The magnetic field induced on Ganymede is further proven by this data. Charged electrons and ions around a planet, and in this case moon, are a main characteristic of a magnetic field and the current sheet. This also allowed us to see the interactions of Jupiter's plasma field and Ganymede's magnetic field, and that there are a significant amount of electron and ion interactions with the magnetic field and the Galileo spacecraft compared to other dates.

3.2.2 05/04/1997

There are many interactions for this date. As shown on the plasma field data, figure 23a, there are high frequencies of interactions on the day before 05/04/1997, and on 04/04/1997.

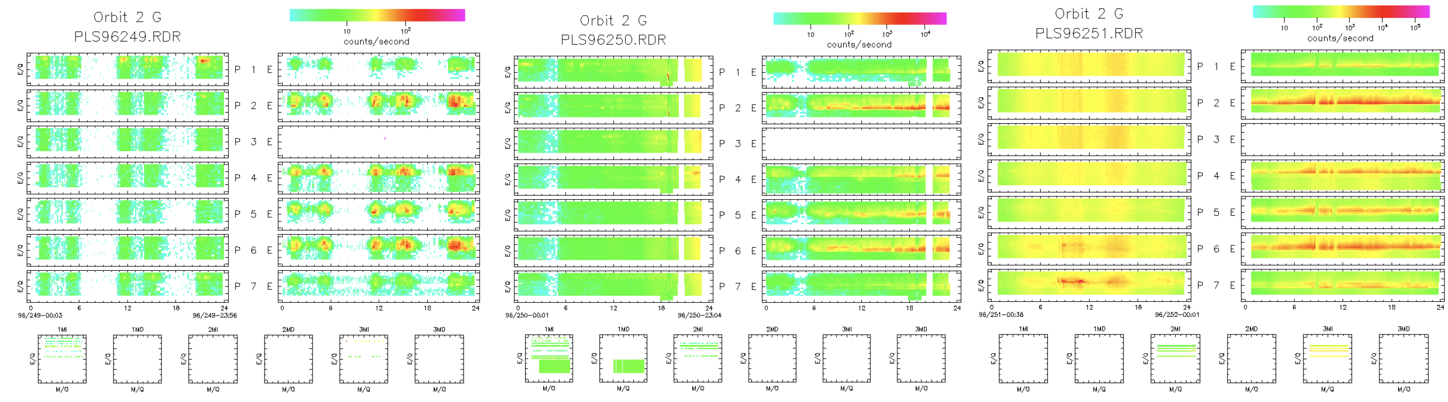
When passing Ganymede, the detector for the plasma field showed an increase in counts per second, from 10^3 to 10^4. This dramatic increase will have caused a lot of interactions involving the electrons and ions in Ganymede's atmosphere. This is represented in figure 24a, 24b, and 24c. In figure 24a it is noticeable that there is a large number of counts for high energies - around 10eV and above. There also seem to be gaps in all of the graphs for energies, this could be due to the aftermath of the increase in interactions, which could cause dropouts due to high-energy electrons that cannot be accounted for.

It is prominent that there is a lot of variation in the electron densities at different radii. During these times, the probe flew a lot closer to Ganymede, and we can see intrinsically small changes at different radii. At Ganymede, when the figure 25 x-axis is at $15R_J$, we see a large spike in the electron density. This indicates that the electrons in the magnetosphere are densely packed in this region. Ganymede is also known to have a very thin oxygen atmosphere, which may be the explanation for the electron density spike, as the electrons will be interacting and becoming trapped in the atmosphere. The peak electron density at the distance of Ganymede from Jupiter is 13.79 ± 0.5 cm^{-3} at 14.9 ± 0.5 $15R_J$. This spike in electron densities, and electron and ion energies are clearly observed, indicating that Ganymede's magnetic field is either interacting or has interacted with Jupiter's plasma sheet.

4 DISCUSSION

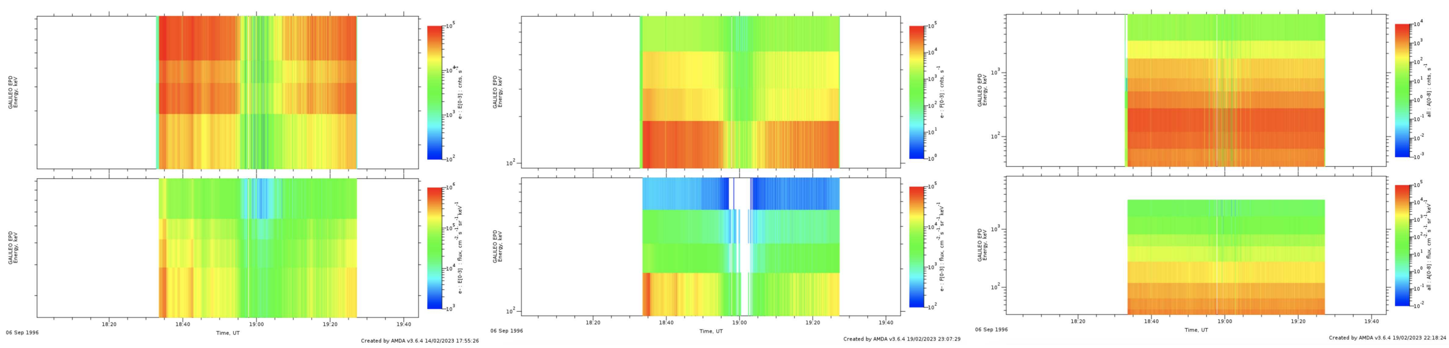
Within our research, we found the magnetic field strengths of both Ganymede and Jupiter, at different regions on their surface, and produced code in order to present this information visually. The simulation allowed us to alter the distance in which we viewed these magnetic field strengths, and notice the difference that distance makes. We explored the strength of Ganymede's magnetic field at its poles in comparison to the equator, where it was measured at 1670 ± 90 nT and 700 ± 20 nT respectively. This result proves the assumption we initially made - that Ganymede can be approximated as having a magnetic dipole. This is clear, as the magnetic field strength was much stronger at the poles of the moon than at the equator. To find this information, we used data from flybys of Ganymede to remove the magnetic field reading contributions of Jupiter's magnetosphere.

Charged electrons are a main characteristic of a magnetic field, and with the results, we have collated, we are further backing that there is a magnetic field present on Ganymede. We found a large amount of electron flux, from 227.5 ± 0.5 cm^{-3} on 06/09/1996, and 13.79 ± 0.5 cm^{-3} on 05/04/1995. There were also large amounts of interactions with Jupiter's plasma field at this time, shown by the spikes in energy in electrons and ions. These energy spikes can be seen in the "drop-offs" in the 1996 and 1997 data, where our understanding leads us to believe that there were electrons present with energies higher than 884keV, that the



(a) 05/09/1996 (b) 06/09/1996 (c) 07/09/1996

Figure 20. Plasma interactions around Ganymede during its fly-by on 05/09/1996, 06/09/1996, and 07/09/1996 using the Plasma Instrumentation (PLS) onboard the Galileo spacecraft. The color spectrum shows the number of counts per second (s^{-1}) the x-axis is the time of the full day on the given date on both sets of graphs. In the left-hand set of graphs, the y-axis is the energy-per-unit charge (E/Q) in the range of 0.9V to 52kV. In the right-hand set of graphs, the y-axis is the energy of the particles in the range of 40eV to 43keV. (NASA 2022a)



(a) E(0-3) Electrons (b) F(0-3) Electrons (c) A(0-8) Ions

Figure 21. The left graph shows electron energies of the classification E(0-3) where the energies have the range of 15 to 93 keV. The middle graph shows energies of F(0-3) electrons, where the energies have the range of 93 to 884keV, on 06/09/1996. On the right, the graph shows ions of the classification A(0-8), where the energies are of the range 22 to 82000keV, and the M, the atomic number, is greater than or equal to 1 and 4. All of this data is from 06/09/1996. Time is on the x-axis and energy is in keV on the y-axis for all graphs. The top graphs have a spectrum due to the number of counts per second (s^{-1}) and the bottom graphs have a spectrum due to the flux ($cm^{-2}s^{-1}sr^{-1}keV^{-1}$).

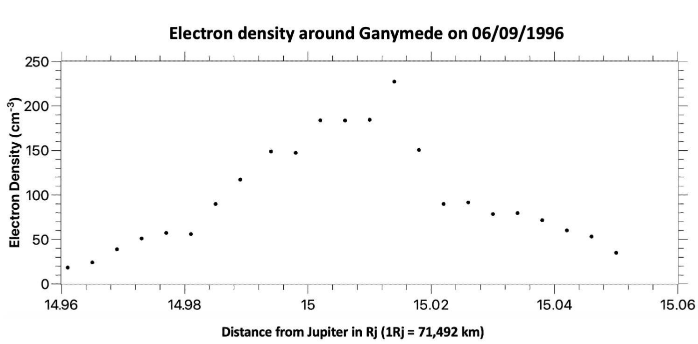
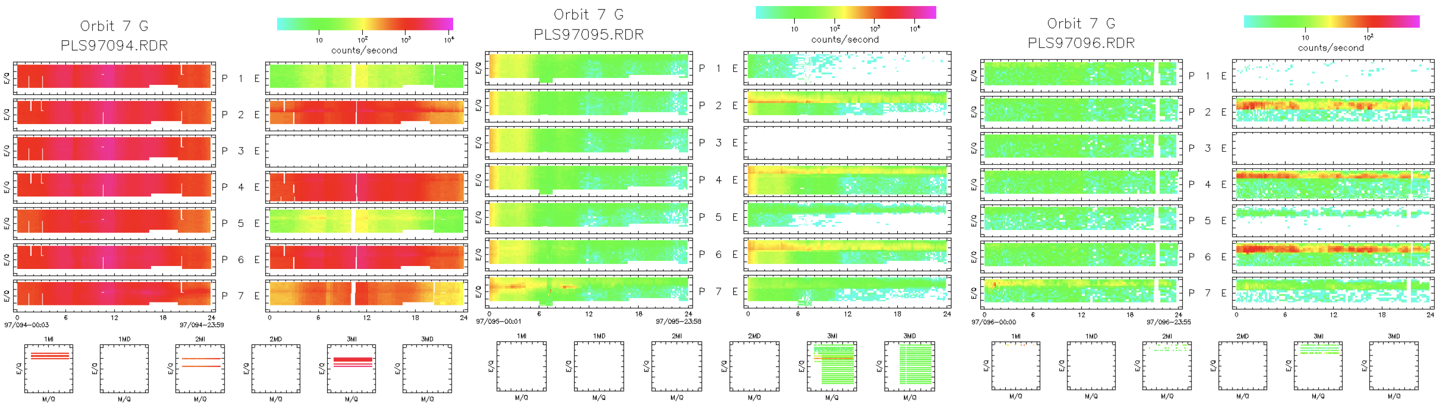


Figure 22. The electron density of Ganymede from Galileo's flybys on 06/09/1996. With distance from Jupiter, in Jupiter Radii where Ganymede is $15R_J$ away, along the x-axis, and the electron density in cm^{-3} along the y-axis.

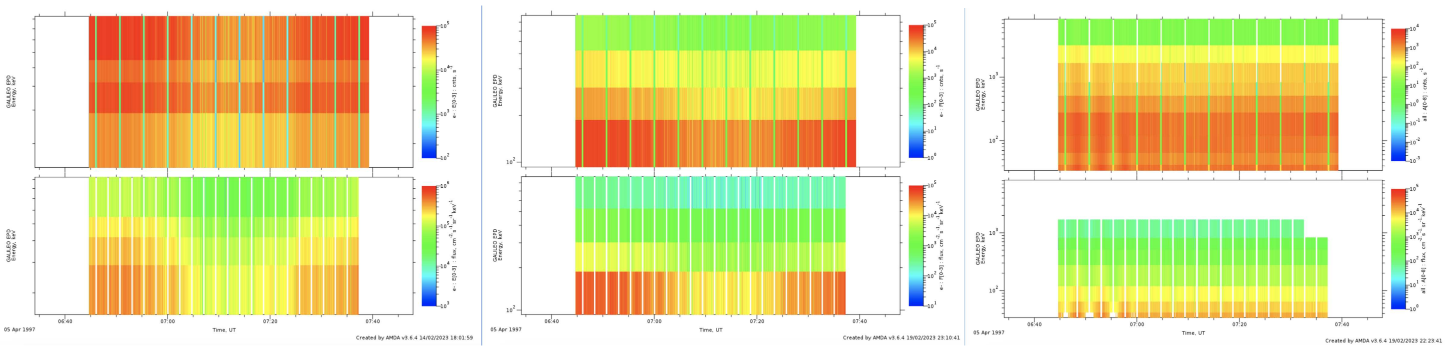
detector could not pick up. When high-energy electrons and ions interact with the magnetic field, they can be lost to the atmosphere and cause interactions in the magnetosphere. One of the most well-known phenomena is aurora, which in Ganymede's case would give off green colors due to the oxygen present in its atmosphere. These charged particles would also fall from the atmosphere and cause weathering on the surface of Ganymede. Charged electrons and ions are important to our understanding of the interactions in the magnetic field and how external environments can shape our data.

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. This limitation was present when investigating the magnetic field strengths at the surface of Ganymede, at the poles, and the surface. There was only one flyby that flew close to the pole of the moon, and one that flew close to the equator.



(a) 04/04/1997 (b) 05/04/1997 (c) 04/04/1997

Figure 23. The figure presents plasma interactions around Ganymede during its flyby on 04/04/1997, 05/04/1997, and 06/04/1997 using Plasma Instrumentation (PLS) built into the Galileo spacecraft. The color spectrum shows the number of counts per second (s^{-1}) the x-axis is the time of the full day on the given date on both sets of graphs. In the left-hand set of graphs, the y-axis is the energy-per-unit charge (E/Q) in the range of 0.9V to 52kV. In the right-hand set of graphs, the y-axis is the energy of the particles in the range of 40eV to 43keV.



(a) E(0-3) Electrons (b) F(0-3) Electrons (c) A(0-8) Ions

Figure 24. The left graph presents electron energies, classification E(0-3), 15 to 93 keV. The middle graph presents F(0-3), where the energies have the range of 93 to 884keV, on 05/04/1997. On the right, the graph shows ions, classification A(0-8), energies 22 to 82000 keV, and M, the atomic number, is greater than or equal to 1 and 4, on 05/04/1997. Time is on the x-axis for all graphs and energy in keV is on the y-axis for all graphs. The top graphs have a spectrum due to the number of counts per second (s^{-1}) and the bottom graphs have a spectrum due to the flux ($cm^{-2}s^{-1}sr^{-1}keV^{-1}$).

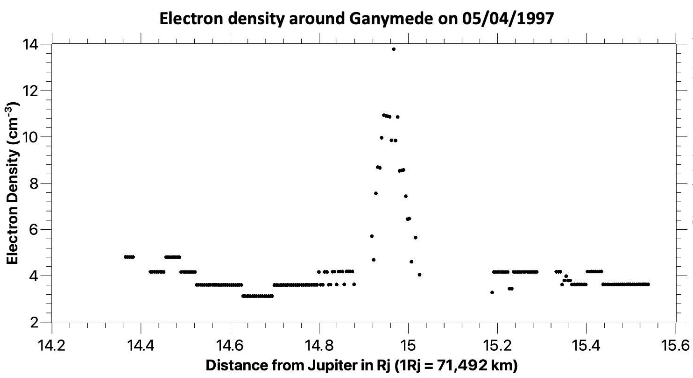


Figure 25. The electron density of Ganymede from Galileo's flybys on 05/04/1997. With distance from Jupiter, in Jupiter Radii where Ganymede is $15R_J$ from Jupiter, along the x-axis and the electron density in cm^{-3} along the y-axis.

To extend the research further, we could create a simulation presenting the path of a charged particle in Ganymede's magnetic field, to visualize how the particle and field would interact. We could also investigate the aurora on the moon, and the links between this aurora and the magnetic field present on Ganymede. As well as this, we could enquire into the effects created by the ocean present under Ganymede's surface, on the moon's magnetism, similar to what Crary and Bagenal did in their paper, 'Remnant Magnetism and Ganymede's Internal Magnetic Field' (Crary & Bagenal 1996).

5 CONCLUSIONS

Ganymede's magnetic field was not the only motivation for this research, we also wanted to understand the charged particle interactions present within the Jovian moon's atmosphere.

To investigate the magnetic field strengths on Ganymede's entire surface, which involved understanding JSO and GPhiO coordinate systems, we used the May and December 2000 flyby. We measured the magnetic field strength to be 700 $\pm$ 20 nT at the equator - with a combined error of 2.67σ away from the expected value of 820 $\pm$ 40 nT - and 1670 $\pm$ 90 nT at the poles - with a combined error 2σ away from the expected value of 1400 $\pm$ 100 nT. These results present the field strength at the poles to be a lot stronger than at the equator, which correlated with our simulation. Initially, we considered Jupiter to have a magnetic dipole when investigating the effects that Jupiter's magnetosphere had on Ganymede. However, our simulation made it clear that Jupiter's magnetic field could only be approximated as a dipole at large distances, and was actually very complicated at shorter distances, closer to the surface.

A limitation of this section of research was that there was only one flyby that flew past the equator and pole of Ganymede respectively, however, the difference in measurements of the magnetic field strength proves that there is a field on the Jovian moon, which motivates this research further.

Now that a magnetic field is established, we theorized that there will be discrepancies due to the day side and night side of the magnetic field. We calculated these values to be 110.9 $\pm$ 0.9 nT for the night side and 99 $\pm$ 1 nT for the day side. These results are unusual and not expected, as we thought the day side strength would be stronger than the night side. We predicted this because the day side of Jupiter's magnetic field is compressed by solar interactions, meaning the magnetic field lines are closer together, and hence the field strength is stronger. One reason for this could be the lack of values for the night side, causing an inaccurate reading of the magnetic field, in addition to there only being one date that shows the day side and night side of the magnetic field. Further work on this research would be to investigate the effects of these discrepancies in more detail.

Galileo only completed six flybys of Ganymede. This gives a limited amount of data to work with. For future work, we could compile all data recorded from every spacecraft that completed a flyby of Ganymede, as this would expand the amount of useful data significantly.

The next part of this paper contained the interactions between the Ganymede and Jupiter, by analyzing charged ions and electrons from Galileo's PLS, PWS, and EPD detectors. The dates 06/09/1996 and 05/04/1997 have plasma interactions with the magnetic field, causing spikes in electron and ion energies. There are dips at certain times in the energies and fluxes of the electrons, in particular, the F(0-3) electrons, where higher energies are found. This was theorized to be due to high energy interactions with the plasma sheet, causing electrons to become more energized than previously, and not being able to be detected. This is further backed up by the fact that there are peaks in the electron densities, 227.5 $\pm$ 0.5 cm^{-3} on 06/09/1996 and 13.79 $\pm$ 0.5 cm^{-3} on 05/04/1995, demonstrating that these electrons are not lost to the atmosphere of Ganymede. The use of other flybys of spacecraft may have opened up more knowledge to the interactions of Ganymede's magnetic field, in addition, a look into aurora produced due to the interacting electrons would have further proved plasma interactions as well as the presence of oxygen in Ganymede's magnetic field. More research linking to weathering on the surface could be utilized to understand the effects that the impact of electrons leaving the atmosphere and hitting the surface would have.

Overall, the investigation confirms a magnetic field on Ganymede, an unusual phenomenon for a moon, through real observations and calculations using Galileo and simulations run in python. Characteristics like energetic electrons and ions are present to further illustrate this. There are many unanswered questions about Ganymede, but its relationship with its host planet is forever entwined, through magnetic fields, plasma interactions, magnetic compression, and impacts on the surface.

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Date (DD/MM/YY)	X value (Jupiter Radii)
27/06/1996	13.0
06/09/1996	13.6
15/11/1996	13.6
27/06/1997	11.8
18/09/1997	10.2
07/11/1997	10.2
16/12/1997	9.7
10/02/1998	9.7
29/03/1998	9.7
31/05/1998	9.7
21/07/98	9.7
26/09/98	9.7
22/11/1998	9.6
01/02/1999	10.6
04/05/1999	11.5
02/07/1999	9.1
12/08/1999	9.1
14/09/1999	9.1
11/10/1999	8.4 (higher y)
26/11/1999	9.6 (higher y)
04/01/2000	10.5 (higher y)
23/02/2000	11.5 (higher y)
21/05/2000	9.7 (slower decrease of x)
29/12/2000	11.8 (slower decrease of x)
23/05/2001	-13.0
05/08/2001	-11
15/10/2001	-8.6
17/01/2002	-7.4

Table A1. Values of positive and negative x values close to when y is 0, dates are to the range of 27/06/1996 to 17/01/2002.

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APPENDIX A: COORDINATES OF FLYBY

Shown in A

APPENDIX B: 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-LancasterUniversity/IMAGINE/tree/main/Data%20Python%20Scripts/GanymedeIsolation.

APPENDIX C: MODELLING JUPITER AND GANYMEDE'S MAGNETIC FIELD

Python script(s) for modelling the magnetic fields of Jupiter and Ganymede: https://github.com/search?q=ankit+barik&type=code.

Feedback comments

Presentation: Good report structure and writing style, although some jumping between topics means the report could have been more concise. Well presented figures with self-contained captions (but please avoid starting captions with 'The Figure'). Some more references to other studies of flybys would have been useful.

Motivation: Abstract is generally well-written but the last three sentences should be more specific (day/night side of Jupiter; strengths of Jupiter's magnetic field; what plasma interactions). Motivation well described in introduction. Future work description needs to be more detailed and related to these results.

Content: The method is well described but some details are missing (e.g. internal field model, measuring total/background-subtracted field in different sections, times of closest approach, effect of both colatitude and distance varying). Key results are stated and shown in graphs. A table of flyby info would have been useful. Results are analysed to varying depth: the analysis of the Ganymede magnetic field magnitudes is more detailed than the plasma interactions.

Understanding: The discussion and interpretation shows some insight but would be improved by more explanation of what is meant by plasma interactions, and the variability of fluxes measured, and what could cause differences in the magnetic field strengths measured. There is little discussion or comparison of these results to other studies, e.g. magnetic field strengths (Jupiter and Ganymede field), detailed flyby studies, interpretation of plasma measurements.