Investigating Magnetic Interactions of the Galilean Moons with Jupiter Using Dipole Field Models

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ABSTRACT

Moons can affect the magnetic environment of their planets by many mechanisms, one being from magnetic fields generated by the moon's interior, another interactions with the external plasma environment. In this project we focused on the former by looking into the magnetic interactions of the Galilean moons with Jupiter. Magnetic field data from the Galileo spacecraft was used to determine the magnetic dipole moments of three of the Galilean moons in order to compare their magnetic fields quantitatively. The fields of the moons were modeled as simplified versions of the most accurate models from previous studies. Induced field models were used for Io and Europa, with dipoles anti-aligned to the Jovian field external to them. The value of the magnetic dipole moment of Io obtained was $7.53 \pm 0.96 \times 10^{12}\,\mathrm{Tm}^3$ and Europa was found to have a magnetic dipole moment of $14.89 \pm 4.71 \times 10^{11}\,\mathrm{Tm}^3$, whilst using the model of an induced dipole. Both are in good agreement with expected values found in the literature. Using a dipole aligned with Ganymede's rotational axis, it was found to have a dipole moment of $1.15 \pm 0.07 \times 10^{13}\,\mathrm{Tm}^3$, nearly in agreement with literature. Magnetopause crossings were identified in the data, as well as perturbations from Jupiter's equatorial current sheet. Overall, the field models used were found to be of expected accuracy to reality, implying that Io and Europa have induced fields while Ganymede's is primarily intrinsic. However, other models for each moon would have to be compared to see what best fits the data.

Key words: Magnetosphere, Magnetic field, Dipole field, Galileo, Io, Europa, Ganymede, Callisto

1 INTRODUCTION

The four Galilean moons of Jupiter are found to be Ganymede, Europa, Io and Callisto, and the way they each interact with Jupiter's magnetosphere is different. To fully understand the interactions, the first step is to understand the way in which Jupiter's magnetosphere is formed, and its shape. Initially, to maintain a stable magnetosphere there must be a strong enough magnetic field to halt the solar wind; a plasma source either internal or external to the magnetosphere to populate it; and an energy source to power it (1). Jupiter's magnetosphere is rotationally driven meaning most of the energy is from the planet's rotation. Whereas plasma is derived from the planet or a satellite of the planet (1). Jupiter's interior contains a strong dynamo that produces a surface magnetic field in the equatorial region with an intensity of approximately 4 Gauss (1). The result of this strong magnetic field combined with Jupiter's fast rotation is a unique magnetosphere. The majority of its plasma is collected from its moon Io, and consists of various charge states of sulphur and oxygen which causes an inflation in the magnetosphere from the combined actions of centrifugal force and thermal pressure.

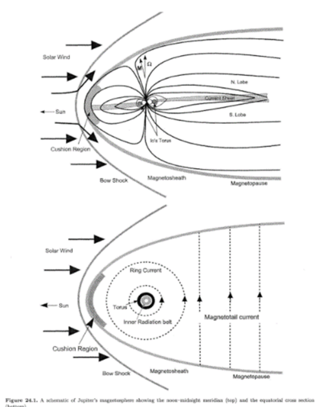

Figure 1. This figure demonstrates the different sections of Jupiter's magnetosphere and the way in which it is formatted(1).

In the thin current sheet located near the equatorial

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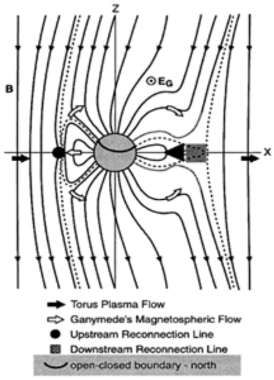

Figure 2. This figure demonstrates the form of the field and flow in the vicinity of a magnetized moon such as Ganymede. It is in a plane containing the unperturbed plasma velocity and the spin axis with the observer viewing from outside the moon's orbit looking radially inward towards Jupiter (2).

plane of Jupiter, the azimuthal currents (currents which are at a horizontal to due north) are very large and create magnetic field perturbations which are comparable in magnitude to the internal field beyond a radial distance of approximately $20\,R_J$. The plasma of the current sheet also begins to exceed unity, meaning that they start to stretch and bend, beyond this distance. Within this region, the magnetic field becomes highly stretched as it attempts to contain the plasma against the strong centrifugal and thermal pressure forces.

To be able to accurately compare how each moon interacts with Jupiter's magnetosphere, it is important to determine the way the region around each moon is perturbed. Firstly, Ganymede is unexpectedly found to have a permanent dipole moment with equatorial field magnitude of 719 nT (2). In this case the internal and external fields are nearly anti-parallel and can reconnect near the moon's equator to produce a magnetic configuration that is reasonably well approximated by the schematic in Figure 2. Ganymede's magnetic field surface strength is 15 times the strength of Jupiter's magnetosphere at the moon's orbit (3)(4). Galileo's observations of Ganymede suggest the interior has a fully formed metallic core, silicate mantle and an icy outer layer. The existence of a substantial magnetic moment appears to indicate that a portion of the central core is fluid and convecting (5).

The field magnitude increases upstream of Europa, consistent with slowing of the flow and increasing pickup (6). A dipolar magnetic perturbation was observed in the magnetic field data from Galileo's initial pass by Europa (7) and the possibility of an inductive response (8) seemed probable. After further passes, it was established that the magnetic moment changes sign in phase with the changing sign of the Jovian magnetosphere's radial field. This observation provided compelling evidence of a global scale conducting shell which could carry a substantial electrical current located within around 100 km of the surface (6)(9)(10)(11)(12). The inductive magnetic moment, along with the measurements, is of the order of the maximum inductive response for a conducting sphere of radius R_E. It must lie close to the surface, as the strength of the signal decreases with the cube of the ratio of the conducting shell to the distance from the centre of the moon. If the conducting shell has the conductivity of terrestrial seawater, the shell would have to be approximately 10 km thick. Because the existence of liquid water is viewed as a desirable, if not necessary, property of a life supporting environment, there is great interest in seeking further evidence that could establish unambiguously if such a layer is present and how deeply it is buried (13).

The Galileo magnetometer detected a field decrease of nearly 40% of the background Jovian field at closest approach to Io during an inbound pass of the Galileo spacecraft. This suggests the presence of an internal magnetic field, as plasma sources alone are incapable of generating perturbations as large as those observed. (Simulations did not match observations when using a non-magnetised but conducting Io whereas they did when using a magnetised one. It is not clear whether this is from is an induced magnetisation or a self-sustained dynamo field). Io's orbital position controls decametric radio emission from Jupiter's ionosphere (14). It was suggested that these emissions were generated by magnetic field-aligned currents linked to Alfvénic disturbances generated by the interaction of the flowing plasma of Jupiter's magnetosphere with an electrically conducting Io (15). Closest approach of the spacecraft was at an altitude of 898 km. All three components of the background Jovian field measured on Galileo's trajectory through the plasma torus followed predictions based on Voyager-epoch magnetic field models (16). In the wake of Io (downstream in the flow of torus plasma co-rotating with Jupiter), the field magnitude decreased by 695 nT in a background of 1835 nT. Perturbations of the field along the spacecraft's trajectory were anti-parallel to the model Jovian field. These perturbations are quite well represented by a model in which Jupiter's field is merely added to the field of an Io-centred dipole. A magnetohydrodynamic (MHD) simulation of the current-carrying region as a conducting, spherically symmetric body of Io's dimensions produced a field depression similar to the actual data, but its magnitude was too small. Larger perturbations are obtained if currents flow through an extended, gravitationally bound Io ionosphere. The MHD simulations assuming Io was demagnetized but conducting did not match the readings made by Voyager 1 (17) unless they made Io have a radius of $1.4\,R_{Io}$ (radius of Io, 1821 km). An internally generated magnetic field was considered as the source of the perturbation as this is expected to align closely with the local field of Jupiter whether the source is an induced magnetisation or a self-sustained dynamo field. Using a magnetised Io in the MHD simulations gives a perturbation of the required direction, size, and spatial scale near the wake center, along the Galileo orbit.

Little is known about Callisto's internal properties. On 4th of November 1996 Galileo had its closest approach to Callisto. Low resolution magnetic field (18) (Δt=24 s) and particle data were acquired as well as 45 minutes of full resolution magnetic field (Δt=0.33 s) and plasma data in the close vicinity of Callisto. The closest approach occurred near 13:34:30 UT at 1.47 times the radius of Callisto ($1.47\,R_C$; R_C=2,403 km) at a latitude of 13° with respect to Callisto's

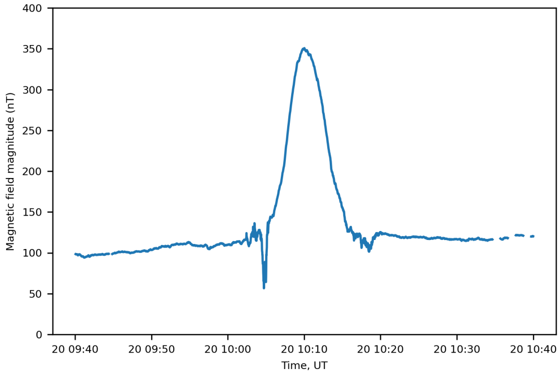

Figure 3. Magnetic field magnitude (nT) measured by the Galileo spacecraft plotted against time, time frame 09:40 – 10:40 on day 2000/05/20, the G28 Ganymede flyby

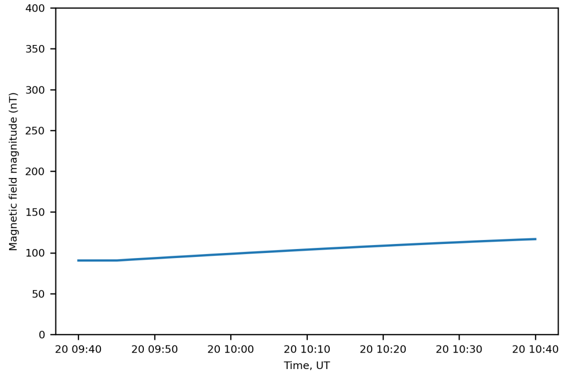

Figure 4. Data from the JRM33 + Con2020 Jovian Magnetic Field Model, timeframe 09:40 – 10:40 on day 2000/05/20

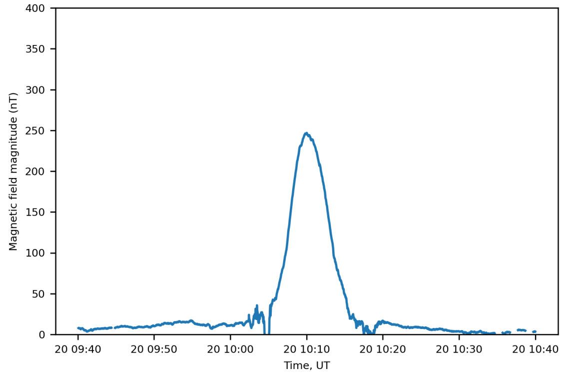

Figure 5. Magnetic field magnitude (nT) measured by the Galileo spacecraft corrected using data from the JRM33 + Con2020 Jovian Magnetic Field Model plotted against time, timeframe 09:40 – 10:40 on day 2000/05/20

equator. The Jovian plasma at this distance (19) moves slower than corotational velocity of 330 km s^{-1} but has a velocity of 200 km s^{-1} and therefore continuously overtakes Callisto, forming a wake. There is an effective dipole moment which has perturbations believed to be caused by the interaction of Callisto with the magnetized plasma. This leads to the belief that, due to Galileo's magnetic field observations, Callisto is in fact demagnetized and possibly has no conducting interior. This discovery is plausible in view of the report by Anderson et al. (20) that Callisto is probably completely undifferentiated and therefore devoid of a convecting core that could support the generation of an internal magnetic field. The purpose of this project is to determine the magnetic moment of Io, Europa and Ganymede. This is completed by determining the area of effect of the induced magnetic field and using this to plot a graph in which the gradient is equal to the magnetic moment. This is a very useful result as it helps to determine which model is accurate in describing the magnetic field of each of the moons. It helps to determine whether the magnetic field is intrinsic or induced, as well as if the induced field is that of a dipole or a shell. This in turn is then used to help determine the interior of the moons and what it is made of.

2 METHODOLOGY

2.1 Correcting magnetic field measurements using analytical models of Jupiter's field

When using magnetic field measurements of the Galilean moons from spacecrafts such as Galileo, Jupiter's magnetic field has to be considered. Jupiter's magnetic field is approximately twenty times larger than that of Earth's, so you can expect that it would affect the measurements for the magnetic field drastically. Galileo measurements of the magnetic field magnitude for the G28 flyby are shown in Figure 3. The graph has a clear peak to 350 nT in magnetic field magnitude from when the spacecraft entered the moon's field, then returns back to 100 nT when the spacecraft leaves the field. This base value that the field returns to, can be assumed to be Jupiter's unperturbed magnetic field. We can approximate Jupiter's magnetic field magnitude to be around 100 nT at the spacecraft's position. A visualisation of Jupiter's magnetic field using an analytic model, such as the JRM33 + Con2020 Jovian Magnetic Field Model is represented in Figure 4. From the graph we can observe that Jupiter's magnetic field at the spacecraft's position is around 100 nT, with a slight increase to around 120 nT as the spacecraft approaches Jupiter. If we wanted to plot the magnetic field magnitude of one of the Galilean moons, a correction could be made to remove the effects of Jupiter's magnetic field. This could be done by simply subtracting 100 nT from every value of the magnetic field magnitude but these will result in inaccuracies and would not consider the slight increase of Jupiter's magnetic field at the spacecraft's position. What can be done instead, shown in Figure 5, is subtracting the analytical model itself from the magnetic field magnitude measured by Galileo. Now the graph begins on 0 nT, peaks at approximately 250 nT and returns back to 0 nT. This is more of what you would expect from the magnetic field magnitude from the moon, and even accounts for the slight increase in Jupiter's magnetic field. The data has now been corrected to account for Jupiter's magnetic field.

The analytic model we used for Jupiter's magnetic field was the JRM33 + Con2020 Jovian Magnetic Field Model. This is a combination of the two models, JRM33 (Connerney et al., 2022) for the internal field and Con2020 (Connerney et al., 2020) for the external field. The first model, JRM33 or 'Juno reference model through perijove 33'(21)(22), was obtained from vector magnetic field measurements taken by the Juno spacecraft during the first 33 of its orbits of Jupiter. The planetary magnetic field is represented as a spherical harmonic, with coefficients of degree and order 13, extending through degree 18. Well fit by a Lowes' spectrum with a dynamo core radius of $0.81\,\mathrm{R_J}$, which represents the outer radius of the convective metallic hydrogen region. This model is not too important for what we are doing as this model provides a detailed view of the planetary dynamo of Jupiter, we are more interested in the external magnetic field. The second model, Con2020 or Connerney et al. (2020) magnetodisc model, uses magnetic field data from 6 to $30\,\mathrm{R_J}$ and System III latitudes from -68 to +40 degrees of Juno's first 24 orbits. The model is defined by seven key parameters: the inner radius of the current sheet, outer radius of the current sheet, half-thickness, the tilt, the azimuthal angles of the surface normal of the current sheet and the azimuthal current parameter. The magnetodisc is defined and calculated using inner radius $7.8\,\mathrm{R_J}$, outer radius $51.4\,\mathrm{R_J}$, half-thickness $3.6\,\mathrm{R_J}$, with tilt angle 9.3 degrees, the azimuthal angle 155.8 degrees, and current sheet field parameter 139.6 nT. The model then removes the JRM09 model, which is another model for the internal field, to be left with a model for just the external magnetic field. The JRM33 and Con2020 models are combined to form an accurate model for Jupiter's internal and external magnetic field. The resulting model considers the magnetodisc current sheet, a partial ring current, and magnetopause currents.

2.2 Finding Io and Europa's magnetic moments

To compare the behaviour of each moon's magnetic field quantitatively, the magnetic moment of each moon's field can be found. As discussed in section 1, the moons Io and Europa are known to have an induced magnetic field. To find the magnetic moment of such moons, their fields can be modelled as a dipole, where the magnetic field is calculated using the equation:

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

Equation 1 (23) gives the magnetic field strength around a magnetic dipole. B is the magnitude of the magnetic field, M the dipole magnetic moment strength, r the radial distance from the dipole, and θ the angle between the vector from the dipole to the point being measured and the magnetic moment vector.

Measurements of the local magnetic field vector, taken by the Galileo Magnetometer as the spacecraft underwent a flyby of the moon, can be used in conjunction with ephemeris data of the position of the Galileo spacecraft relative to the moon to find the dipole magnetic moment (M) for that flyby. The method used to find M is described below by using a particular flyby (I27 on 22/02/2000) as an example. We repeated this same process for multiple flybys of both Io and Europa to calculate a final average value of M for each moon and our results are given in section 3.

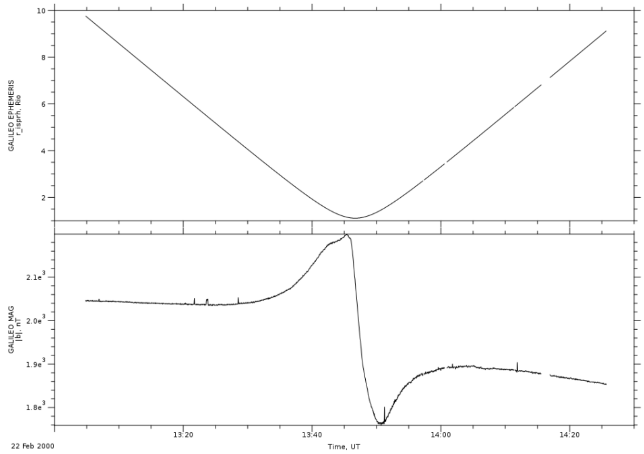

Figure 6. Magnetic field strength and radial distance to Io against time for the I27 flyby of Galileo. Plotted in AMDA to determine the exact start and end times of the flyby in UT.

Firstly, the exact start and end time in Universal Time (UT) for the flyby is determined by plotting the magnetic field magnitude (B) and radial distance to the moon against time as shown in Figure 6. This allows the exact time the spacecraft began and ended recording data during that flyby to be seen. For this flyby and as shown in Figure 6 the time period is 13:05-14:26 UT on 22/02/2000. The raw value of the measured magnetic field vector components (B_x, B_y, & B_z) that the Galileo Magnetometer measured between this time period and at 1 minute intervals, can be taken from the AMDA database (see section 5 for all acknowledgments). The data for the vector components of the background field during this time period is also obtained using the JRM33 and CON2020 model data from AMDA as outlined in section 2.1.

The background field was subtracted from the measured field in order to find B in Equation 1. This removes any perturbations in the measurements of the field around the moon that may have been caused by the background Jovian field rather than just the moon itself. The other important factor to consider that may affect the measured value of the field is the position of the spacecraft relative to the moon as it undergoes its flyby. This is accounted for by the co-latitude angle term θ in Equation 1. θ is defined as the angle between the direction of the position vector $\mathbf{r}$ of the spacecraft relative to the moon and the direction of the induced magnetic field vector. To find the direction of the induced magnetic field vector, all components of the background field vector can be multiplied by -1. This is because the induced field will always be anti-parallel to the field causing it. A schematic defining $\mathbf{r}$, θ and the direction of magnetic fields around the moon can be seen in Figure 7. The background field model uses System III coordinates-which are spherical coordinates centred around Jupiter. However, all ephemeris data in AMDA of the Galileo spacecraft is given in 'moon-centred' spherical coordinates or system III centred around Jupiter (see appendix A). To find $\mathbf{r}$ in the

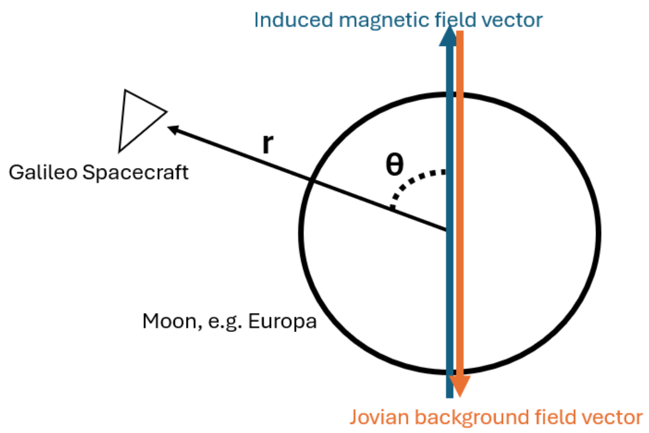

Figure 7. Schematic to show the definition of $\mathbf{r}$ and θ from Equation 1 in relation to Galileo, the moon and the induced magnetic field.

same system as the background field (system III) but centred around the moon rather than Jupiter (to be consistent with the definition of $\mathbf{r}$) we used Python (see section 5 for all acknowledgments) to find the position vectors from Jupiter to Galileo, and Jupiter to the moon, then subtracted the latter from the former to find $\mathbf{r}$.

Now that $\mathbf{r}$ and the induced field vector have been defined properly and found in the same coordinate system, the angle between them can be found using the scalar product formula:

$$cos(\theta) = \frac{\mathbf{a} \cdot \mathbf{b}}{\mid \mathbf{a} \mid\mid \mathbf{b} \mid} \tag{2}$$

where θ is the angle between any two vectors $\mathbf{a}$ and $\mathbf{b}$. The value of θ was computed for each time step of the data. Rearranging Equation 1 shows how θ and B can be used to find M:

$$B_{eq} = \frac{B_{meas} - B_{back}}{(1 + 3\cos^2(\theta))^{\frac{1}{2}}} = Mr^{-3} \tag{3}$$

where θ is the colatitude angle as defined above, r is the radial distance between the dipole (the moon) and the observer (Galileo spacecraft), $B_{meas} - B_{back}$ the corrected measured magnetic field and M the dipole magnetic moment. B_{eq} is the equatorial magnetic field as we have removed the effect the position of the spacecraft relative to the moon has on the measurement of the magnetic field by dividing by the colatitude term.
Plotting B_{eq} against r^{-3}, where each time step in the flyby time frame specified is a different data point on the graph, should show the linear relationship from Equation 3, where the magnitude of the gradient of the line of best fit is M. The magnitude is taken because a negative correlation is expected. This is because the induced magnetic field acts against the background and we should therefore see a negative change in the field as we get closer to the moon. The magnitude of this decrease is therefore what is used to calculate M. The data for r is taken from the Galileo ephermeris data on AMDA.

As shown in Figure 8, a negative correlation can be seen as expected. However, the expected linear relationship breaks down for large values of r. This is because at large values of r, the Galileo spacecraft is no longer within the area of effect

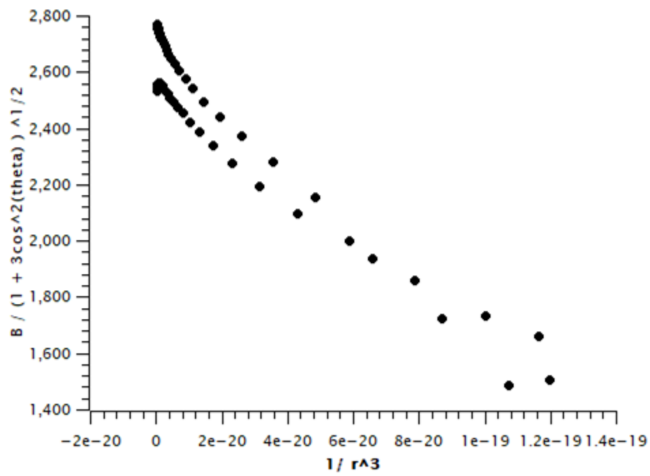

Figure 8. Equatorial magnetic field magnitude in nT against $1/r^3$, where r is the radial distance from Io to Galielo in metres. Flyby I27, time frame 13:05-14:26 on day 2000/02/22. Note this data includes values of r that lie outside the estimated area of effect of the moon.

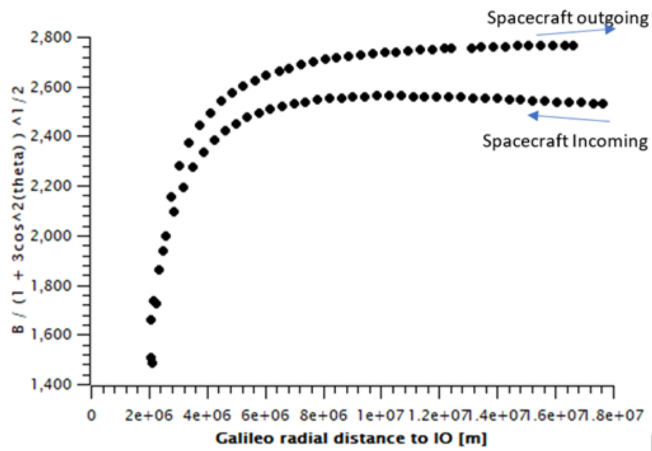

Figure 9. Equatorial magnetic field magnitude in nT against radial distance. Used to find an estimate of the area of effect of the moon's dipole magnetic field. Flyby I27, time frame 13:05-14:26 on day 2000/02/22.

of the induced dipole and therefore the magnetic field cannot be modelled using Equation 3.

Plotting B_{eq} against r, as shown in Figure 9, allows an estimate of the moon's area of effect to be made. The estimated area of effect is taken as the value of r when B_{eq} begins to rapidly drop off. For the particular flyby shown in Figure 9 this was estimated as 6×10^6 m. Figure 8 can then be re-plotted to only include the values of r that lie within this estimated area of effect. This will now show a linear relationship, where the magnitude of the gradient of the line of best fit is calculated to find M. This method of finding the estimated area of effect and plotting B_{eq} against r^{-3}, where the values of r are within the area of effect of the moon, is repeated for multiple flybys of both Europa and Io. This allows an average value of M to be calculated for each moon. Our results, along with the final graph used to calculate M

for each flyby, for Europa and Io are shown in sections 3.2 and 3.1 respectively.

2.3 Finding Ganymede's magnetic moment

Unlike the other moons, it is known that Ganymede has both an intrinsic and an induced magnetic field, the former being much stronger than the latter (2). As the intrinsic magnetic moment is much stronger than the induced one, it was decided to model the field as a dipole with permanent direction with respect to Ganymede. Ganymede's magnetic axis is only 4 degrees from antiparallel from its spin axis (2), so the magnetic moment was taken to be coaxial to the spin axis.

Magnetometer measurements for all passes were used. The measurements were corrected as set out previously, to remove the effects of Jupiter's magnetic field. Ephemeris data of Galileo with respect to Ganymede were used to determine the strength of the magnetic field of the model dipole at Galileo's position, using Equation 1. The magnitudes of the reduced magnetometer data and dipole field model were plotted on the same graph, and the size of the magnetic moment adjusted to best match the peaks of each curve, the result of which can be seen in Figure 19. The intrinsic magnetic moment of Ganymede for that pass was taken to equal this best-fit value.

The uncertainty in this value from Table 3 was taken to equal the maximum error that could have been caused by the angle between the magnetic and rotational axes of Ganymede being taken as zero. To find this, 4 degrees was added to the θ of the spacecraft, then the magnetic moment was recalculated by rearranging Equation 1. The difference between this magnetic moment and our best-fit value was found, then the process repeated, subtracting 4 degrees this time instead. The greater of the two differences was taken as the uncertainty.

3 RESULTS

3.1 Io

Using the method discussed in section 2.2, four different flybys were used to calculate an average value of the magnetic dipole moment M of Io. This used magnetic field measurements from the Galileo spacecraft and ephemeris data of the position of the spacecraft relative to the moon. The four flybys, J0, I24, I27 and I32, which each got within 897 km, 611 km, 198 km and 184 km to Io respectively, were used as these were the only flybys that the AMDA database had data for. As discussed in section 2.2, a plot of B_{eq} against r^{-3} (making sure all values were within the estimated area of effect for the moon) was made for each flyby.

Figure 10 shows the result for the J0 flyby which took place on 7th December 1995. A value of $M = 7.6 \pm 2 \times 10^{12}\,\mathrm{T\,m^3}$ was obtained after removing all values of r outside the estimated area of effect. The error is the error given by the graphing software used to plot the linear fit.

The next flyby (I24), which took place on 11th October 1999 is shown in Figure 11. The value of M obtained from the linear fit for this flyby's data was $6.4 \pm 0.5 \times 10^{12}\,\mathrm{T\,m^3}$.

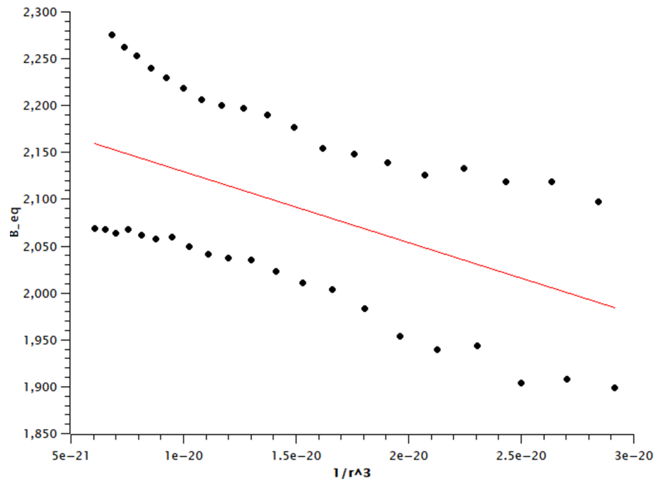

Figure 10. Equatorial magnetic field magnitude plotted against $1/r^3$ for the Galileo flyby J0, where r is the radial distance from Io to Galileo in metres. A linear fit has been plotted to find the value of M from Equation 3. The result result is given in Table 1.

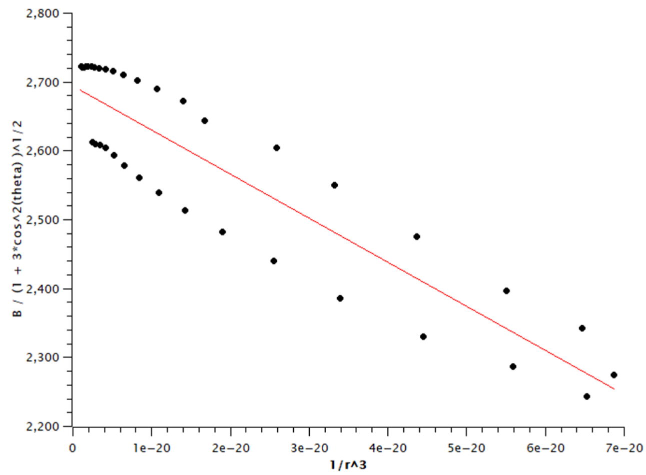

Figure 11. Equatorial magnetic field magnitude plotted against $1/r^3$ for the Galileo flyby I24, where r is the radial distance from Io to Galileo in metres. A linear fit has been plotted to find the value of M from Equation 3. The result result is given in Table 1.

Figure 12 shows the result for the I27 flyby that was used as the example in section 2.2. This is the same data as Figure 8 but with all values of r that lie outside of the estimated area of effect removed. The value of M obtained for this flyby was $8.6 \pm 0.4 \times 10^{12}\,\mathrm{T\,m^3}$.

Finally, the result for flyby I32 is shown in Figure 13. This flyby took place on 16th October 2000 and the value of M obtained was $3.0 \pm 0.3 \times 10^{12}\,\mathrm{T\,m^3}$.

The result for each flyby is summarised in Table 1.

3.2 Europa

When analysing Europa's field we used measurements from flybys of the moon from the spacecraft Galileo. The flybys which were chosen were the E26, E19 and E12 flybys which got within 373 km, 1444 km and 196 km of Europa respectively. For all these flybys we plotted the equatorial

Table 1. The dipole magnetic moment of Io for four different flybys - obtained by performing calculations on magnetic field data measured by the Galileo spacecraft. All data is taken from the AMDA database (see section 5 for all acknowledgements).

Pass	Magnetic moment/10^{12} (Tm^3)	Closest approach (CA) (Io radii)	Latitude at CA (deg)	Magnetic latitude of Io at CA (deg)
J0	7.6 ± 2	0.492	-9.35	3.1
I24	6.4 ± 0.5	0.335	4.51	-5.1
I27	8.6 ± 0.4	0.109	18.3	-4.9
I32	3.0 ± 0.3	0.101	-78.6	5.1

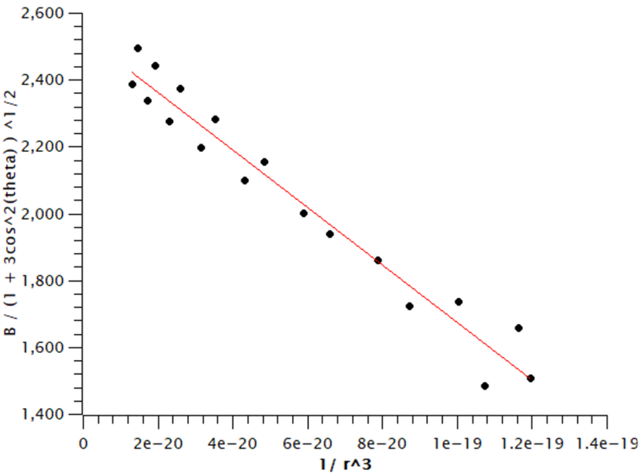

Figure 12. Equatorial magnetic field magnitude plotted against $1/r^3$ for the Galileo flyby I27, where r is the radial distance from Io to Galileo in metres. A linear fit has been plotted to find the value of M from Equation 3. The result result is given in Table 1.

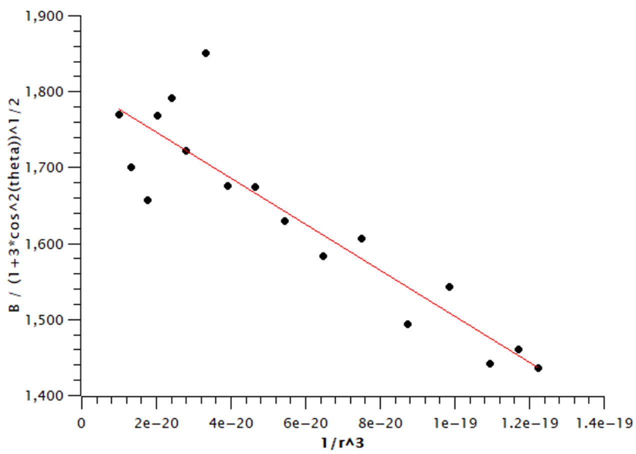

Figure 13. Equatorial magnetic field magnitude plotted against $1/r^3$ for the Galileo flyby I32, where r is the radial distance from Io to Galileo in metres. A linear fit has been plotted to find the value of M from Equation 3. The result result is given in Table 1.

magnetic field magnitude against $1/r^3$, where r is the radial distance from the Galileo spacecraft to Europa. This was to demonstrate the $1/r^3$ relation between the magnetic field and radius. The slope of these plots was calculated and was determined to be the magnetic dipole moment, we could compare the values we calculated to the actual values to demonstrate the accuracy and validity of our method and results.

To do this, we were able to find and select (10) specific readings for the magnetic moment as well as the modelled magnetic moment which was used to be able to compare to. These values provided are data used in a simulation for the upcoming Europa Clipper mission (24). As such, no errors are given so we cannot see agreeableness in our results, only how accurate they are to the provided simulation data. However, in another paper (Table 1 of this article (10)) there are measured values of said magnetic moment which unfortunately also do not have errors given but would give us a reasonable comparison with our results from the AMDA data, seen in Figures 16, 15 and 14. The way we processed the AMDA data was in a progressive manner given that we mainly started with modelling the magnitude of the magnetic field (see Figures 17 and 18) and then moving onto using this data along with other flybys to model the induced dipole around the satellite.

Figure 14 shows the equatorial field magnitude for flyby E26, which took place on the 3rd of January 2000. From the graph, two clear curves can be observed; one for when the spacecraft was approaching Europa and one from when it was leaving Europa. The slope which can be calculated should represent the magnetic dipole moment, though a clear linear correlation does not really occur. The slope was calculated to be $-4.74 \pm 4.72 \times 10^{11}\,\mathrm{Tm}^3$. Taking the magnitude and comparing our value of $4.74 \pm 4.72 \times 10^{11}\,\mathrm{Tm}^3$ to the actual measured value of $5.95 \times 10^{11}\,\mathrm{Tm}^3$, we can see the two values have the same order of magnitude and our value is in excellent agreement as it is within 1 uncertainty of the measured value.

Figure 15 shows the equatorial field magnitude for flyby E19, which took place on the 1st of February 1999. In this graph a more defined curve can be observed, with both the approaching and departing curve having a negative gradient. The slope was calculated to be $-26.61 \pm 5.29 \times 10^{11}\,\mathrm{Tm}^3$. Taking the magnitude of this value we get a value of $26.61 \pm 5.29 \times 10^{11}\,\mathrm{Tm}^3$. Comparing this value to the measured result of $15.1 \times 10^{11}\,\mathrm{Tm}^3$, our value is not in agreement as it is within 4 uncertainties of the measured value.

For flyby E12, which took place on 16th of December 1997 at 11:45-12:15 UT, we were able to obtain the equatorial magnetic field magnitude in T against the radial distance of Galileo in m as $1/r^3$. This allowed us to see the linear relationship that a magnetic dipole has with radial distance and can be seen in Figure 16. The slope was calculated to be $13.31 \pm 4.11 \times 10^{11}\,\mathrm{Tm}^3$. The measured result of another scientist is given by $15.07 \times 10^{11}\,\mathrm{Tm}^3$ comparatively, so our result is between 4 and 5 errors and as such is not agreeable.

Table 2. Europa magnetic moments found from experimental AMDA data of the flybys. Closest approach is the smallest distance of the spacecraft from the moon during the flyby. Latitude is the latitude of the point on Europa's surface Galileo is above. Magnetic latitude is taken from Jupiter's magnetic equator.

Pass	Magnetic moment/10^{11} (Tm^3)	Closest approach (CA) (Europa radii)	Latitude at CA (deg)	Magnetic latitude of Europa at CA (deg)
E12	13.31 ± 4.11	0.126	-8.6	-0.8
E19	26.61 ± 5.29	0.925	31.0	4.8
E26	4.74 ± 4.72	0.239	-46.4	-9.6

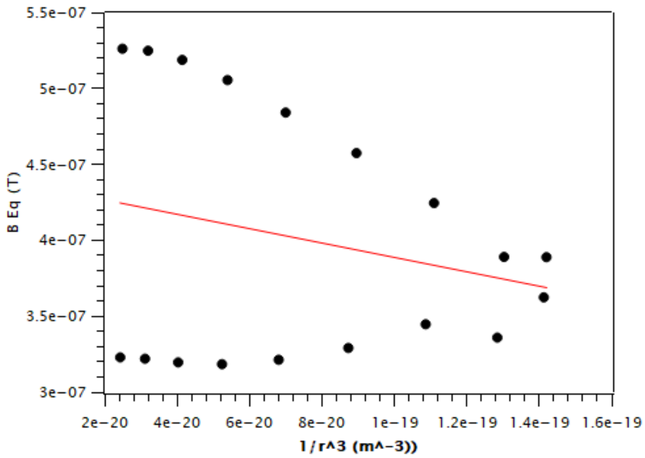

Figure 14. Equatorial magnetic field magnitude plotted against $1/r^3$, where r is the radial distance to Europa from Galileo in m, Galileo flyby E26, time frame 17:30 – 18:30 UT on day 2000/01/03

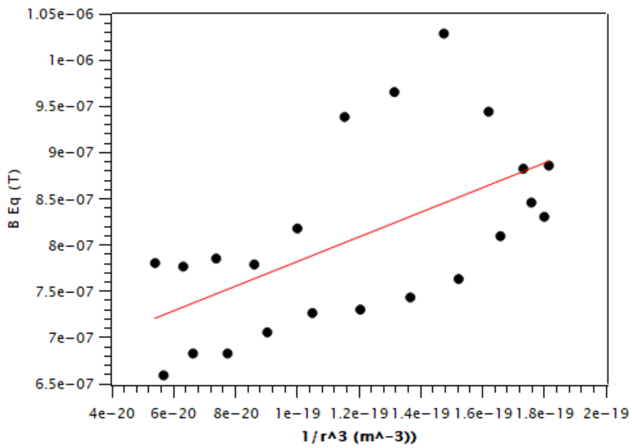

Figure 16. Equatorial magnetic field magnitude plotted against $1/r^3$, where r is the radial distance to Europa from Galileo in m, Galileo flyby E12, time frame 11:45 - 12:15 UT on day 1997/12/16

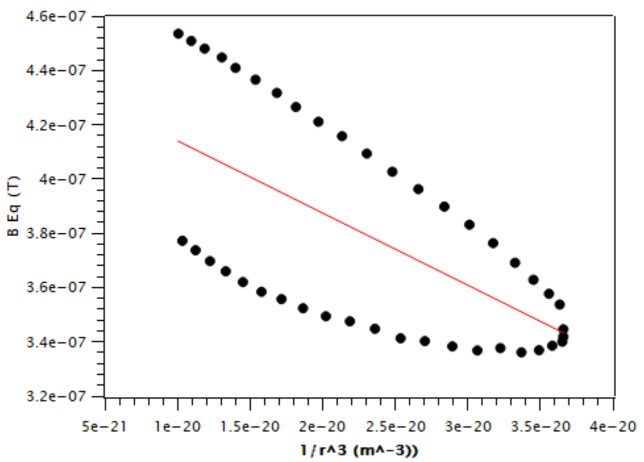

Figure 15. Equatorial magnetic field magnitude plotted against $1/r^3$, where r is the radial distance to Europa from Galileo in m, Galileo flyby E19, time frame 01:45 – 02:45 UT on day 1999/02/01

3.3 Ganymede

The magnetic moments obtained from plots like Figure 19 can be seen for each pass in Table 3. The pass G8 (see Figure 20) has the lowest associated moment, and the noisiest magnetometer readings.

Removing the anomalous 0.59×10^{13} Tm^3 value, the arithmetic mean of these values is 1.15×10^{13} Tm^3. Using Equation 4, the uncertainty in this mean (without using the uncertainties in Table 3) was found to be 0.07×10^{13} Tm^3 .

$$\Delta M = \frac{\sigma_{n-1}}{\sqrt{N}} = \sqrt{\frac{\sum(M_i - \bar{M})}{N(N-1)}} \tag{4}$$

Where M is the magnetic moment magnitude, ΔM is the uncertainty in that magnitude, σ_{n-1} is the standard deviation of the values of M, M_i represents the value for a single flyby, $\bar{M}$ is the mean, and N is the number of values of M being used to calculate ΔM.

The uncertainty was also found from the uncertainties in Table 3 to be 0.02×10^{13} Tm^3, using Equation 5.

$$\Delta M = \frac{\sqrt{\sum \Delta M_i^2}}{N} \tag{5}$$

Where ΔM is the total uncertainty from each individual uncertainty ΔM_i in Table 3, and N is as defined for Equation 4.

The uncertainty in the mean being higher than that calculated from individual uncertainties means the angle between the magnetic and rotational axes of Ganymede is not the main source of error in the magnetic moment values. Ganymede's field being partially induced contributes to this uncertainty, as the external field of Jupiter changes in direction and magnitude relative to the Ganymede's permanent dipole, changing the relative direction of the induced dipole. $1.13 \pm 0.09 \times 10^{13}$ Tm^3 gives a surface equatorial field magnitude of 620±50nT, just within 2 standard deviations of the value found for the permanent dipole moment by Kivelson et al(2).

Table 3. Ganymede magnetic moments found from fitting peaks of the model and data. Closest approach is the smallest distance to Ganymede's centre; latitude is the latitude of the point on Ganymede's surface Galileo is above; magnetic latitude is taken from Jupiter's magnetic equator

Pass	Magnetic moment/10^{13} ($\mathrm{Tm^3}$)	Closest approach (CA) (Ganymede Radii)	Latitude at CA (Degrees)	Magnetic latitude of Ganymede at CA (Degrees)
G1	1.15 ± 0.06	1.32	29.1	8.4
G2	1.31 ± 0.02	1.10	76.1	6.8
G7	1.18 ± 0.04	2.18	55.5	-9.5
G8	0.59 ± 0.03	1.61	28.0	1.1
G28	0.88 ± 0.05	1.31	-18.9	-8.3
G29	1.25 ± 0.04	1.89	61.84	9.0

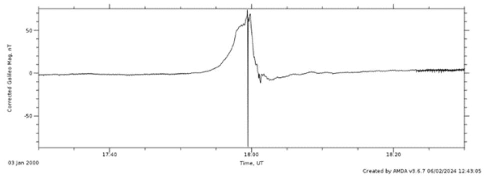

Figure 17. Corrected magnitude of magnetic field of Europa (using model JRM33 + Con2020)

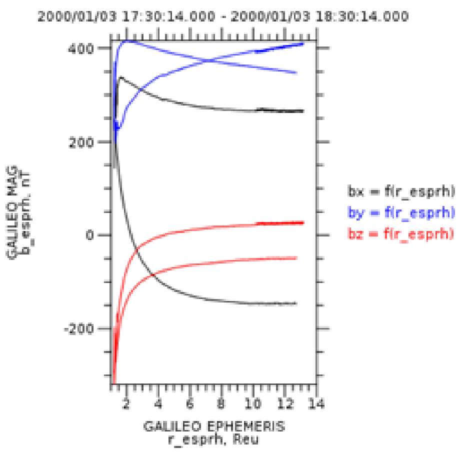

Figure 18. Europa's magnetic field in the ESPRH - spherical Europa-centered 'planetocentric' right-handed coordinates on the y axis and the distance from the spacecraft to Europa on the x axis. R (bx) is along the satellite to spacecraft line, positive away from the satellite. Phi (by) is parallel to the satellite's planetographic equator and positive in a right-handed sense. Theta (bz) completes the right-handed set (positive southward)

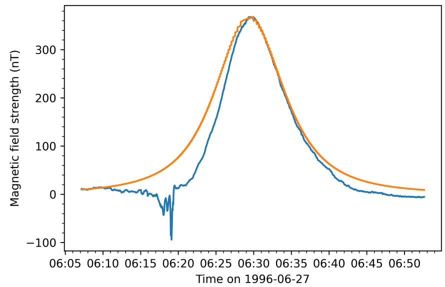

Figure 19. Corrected magnetometer data (blue) and model dipole field (orange) for the G1 pass. The model field uses a moment of $1.15 \times 10^{13}\,\mathrm{Tm^3}$

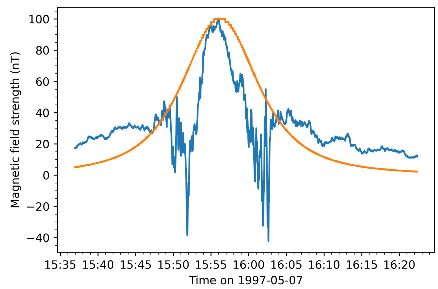

Figure 20. Corrected magnetometer data (blue) and model dipole field (orange) for the G8 pass. The model field uses a moment of $5.9 \times 10^{12}\,\mathrm{Tm^3}$

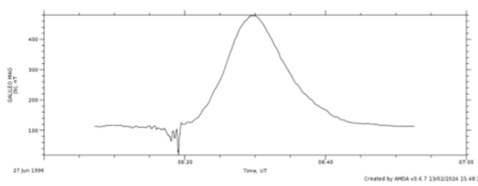

Figure 21. Magnetic field strength measured by Galileo's MAG instrument over time, plotted in AMDA to find start and end of flyby times

4 DISCUSSION

4.1 Io

The expected value of Io's dipole magnetic moment M is $8.0 \times 10^{12}\,\mathrm{T\,m^3}$ (30). The value obtained for the first flyby that was investigated (J0) was $7.6 \pm 2 \times 10^{12}\,\mathrm{T\,m^3}$. The expected value lies within one error of this obtained value of M and is therefore in good agreement with it. However, it is worth noting that the error for this value is much larger than that for other flybys. This could be due to the fact that the data is very clearly separated into two distinct lines in Figure 10. This could be due to slight differences in the background magnetic field as the Galileo spacecraft is incoming and outgoing from the moon. This does not affect the result for M as the gradient of both lines is approximately the same. However, the way in which the error for the linear fit is calculated by the graphing software may be significantly affected by this. To lower the error for this case in the future it may be better to only look at the incoming or outgoing magnetic field data alone. This would, however, half the data sample size which would give less supporting evidence for the obtained value of M. This could be improved by lowering the time step used in the method outlined in section 2.2. By using a time step of 10 seconds rather than 1 minute the number of data points could be six times larger which would yield far better results.

The value of M obtained for the next flyby (I24) was $6.4 \pm 0.5 \times 10^{12}\,\mathrm{T\,m^3}$. The expected value lies just outside 3 errors from this value and is therefore not in agreement - despite the fact they are within the same order of magnitude. This could be due to the estimate for the area of effect of the moon, as discussed in section 2.2, being inaccurate because as seen in Figure 11, at large values of r the graph does not follow the linear relationship that is expected from Equation 3. Another reason why this value is not in agreement with the expected value is due to the model used for the background field. As discussed in section 2.2, the background field is subtracted from the measured field in order to see the field caused by only the moon. If the model were perfect, the magnetic field outside of the area of effect of the moon should be approximately zero. However, as Figure 9 shows this is not the case. This could be due to the fact that the model used does not take into account the other sources of background field perturbations discussed in Section 1 - such as the azimuthal currents in the thin current sheet located in the equatorial plane of Jupiter. As shown in Table 1, the flyby I24 is closest to the equatorial plane as the latitude at CA value is smallest for this flyby. This could be why this result is affected by these other sources of magnetic field perturbations the most.

The value of M obtained for the I27 flyby was $8.6 \pm 0.4 \times 10^{12}\,\mathrm{T\,m^3}$. The expected value lies within two errors and our error is not significantly large like the J0 flyby. This means this value is in good agreement with the expected value. This could be due to Galileo being positioned outside of the equatorial plane (as shown in the Latitude data at CA in Table 1) and therefore away from any other sources of magnetic perturbations unlike the I24 flyby. This flyby also has one of the closest approaches of all the flybys which means almost all of the data points in Figure 12 were within the estimated area of effect and were therefore more likely to follow the expected linear relationship.

The value of M obtained for the final flyby of Io that was investigated (I32) was $3.0 \pm 0.3 \times 10^{12}\,\mathrm{T\,m^3}$. This value is of the same order of magnitude as the expected value, but it is significantly different. This is an unexpected inaccuracy due to the better accuracy of the calculated values of M found for the first 3 flybys. Upon further research into this particular flyby, it was discovered that during this time the Galileo spacecraft had been analysing the outer portions of the newly formed Thor volcanic plume (31). It is reasonable to assume that flying through a volcanic plume and the radiation damage the Galileo spacecraft had obtained over the course of its lifetime significantly affected the validity of the result for this flyby. It is therefore ruled as an outlier in the results and is not counted towards the final average.

After discounting the I32 flyby an average for the first 3 flybys and its error was calculated to be $7.53 \pm 0.96 \times 10^{12}\,\mathrm{Tm^3}$. This is in excellent agreement with the expected value of $8.0 \times 10^{12}\,\mathrm{T\,m^3}$ as the expected value is less than one error away. This result could still be improved further by using the methods discussed earlier to increase the sample size and improve the accuracy of the models used.

4.2 Europa

Looking at the graph shown in Figure 14 from Galileo flyby E26, we can see two different relations of equatorial magnetic field and radius. One of which the gradient is positive and another is negative, this suggests the magnetic dipole moment can differ drastically from when the spacecraft is either approaching or leaving the moon. Therefore fitting a linear relation might not have been the most appropriate choice but we wanted to stay consistent with the method we used for Io. The overall gradient and magnetic dipole moment for this flyby was calculated to be negative, a reason for this may be because the value that was measured was the induced magnetic field, which opposes Jupiter's background field creating a dip or decrease in its magnetic field. For this reason we think it is best to take the magnitude of this value when comparing it to actual results. The error which was calculated for our value for magnetic dipole moment for this flyby was incredibly large compared to the true value, this was probably because of our linear fit of the two opposing gradient relations. Due to this large error, this result is in excellent agreement with the true value. Flyby E19, shown in Figure 15 was a much more sensible relation. The two gradients of when the spacecraft was approaching or leaving the moon were at least both of the same sign, resulting in a much smaller error. The two curves were still quite distant to the linear fit but should still be similar gradients and therefore approximately the same magnetic dipole moments, meaning a linear fit should be appropriate in this case. Once again the magnetic dipole moment was calculated to be negative but taking the magnitude, we can say our value was not in agreement as it was within 4 uncertainties away from the expected value. Figure 16 shows flyby E12, the closest approach of the flybys we used. As we can see the figure shows the relationship being positive compared to both other relationships in Figure 14 and Figure 15. This is due to the orbital period being given as the maximum of the synodic period that Europa has due to the relationship between the primary field of Jupiter and the induced field of Europa. This would mean that the flyby is shown to be on the opposite side of Europa in the given times, when compared to the other relationships seen in the figures. The error for this result was once again not in agreement with the expected value, with it being between 4 and 5 uncertainties. This can be briefly seen in this article (10) in Figure 3, where it shows on a presented graph the relative positions of the flybys with each other. Another note of importance is that on this particular flyby (being one of the two passes to be within 400 km), that was interacting with a plume of ions from within the surface of Europa. As such, the data readings are on the more sporadic side such that even Figure 16 shows a varying range of results such that there may have been some other interference other than the plasma (which was already taken into account). Given that there is no readily accepted value for Europa's magnetic dipole, we calculated a range of values based on the background field fluctuations to be approximately 5-15 $\times 10^{11}$ $\mathrm{Tm^3}$. This would mean that 2 of these flybys were close to this range as well as our averaged value being within this range. However, the range being so large means that many other conditions could be imposed to cause other fluctuations like Jupiter's current sheet.

4.3 Ganymede

Ganymede is the only moon in the solar system known to have a magnetosphere (3), the boundary of which necessarily has a magnetopause, a region of high currents and correspondingly high magnetic field perturbations. In Figure 20, at approximately equal times before and after the peak value of the magnetometer readings, large deviations from the dipole model can be seen - likely caused by Galileo crossing the magnetopause. For G1, Figure 19 shows only a small perturbation on the approach to Ganymede, and no visible perturbation from a smooth curve on exit. If the magnetopause generated the same perturbation at each crossing, and were a sphere centred on Ganymede with the same radius for each pass, one would expect to see perturbations in G1's plot, as in Table 3 G1's approach is closer to Ganymede than G8's. If other positional values in the table are the cause, it is likely the Jupiter magnetic latitude of Ganymede, as G8 puts it deep within Jupiter's current sheet. As in Figure 19, in all plots except for G8 a larger dip in magnetic field strength can be seen upon approach to Ganymede than on exit. As Galileo orbited Jupiter in a single direction for its entire mission, these similarities can be expected, since Galileo would always enter Ganymede's magnetosphere on the side Jupiter's plasma was moving towards, and exit on the side plasma was moving away from. The motion of the corotating plasma and Ganymede's magnetic field generates higher plasma density on the side the plasma flows against than in the wake of Ganymede, which requires higher magnetic fields for a steady-state magnetopause. Therefore this may be the cause of the larger perturbations at the earlier magnetopause crossings than the later ones.

5 CONCLUSIONS

The AMDA data set consisted of four different sets of flyby data for Io during the Galileo mission. Using the method discussed in section 2.2, the magnetic moment of Io can be found for each flyby and the results, along with their errors, are summarised in Table 1. This set of results were then averaged to find a value for Io's magnetic moment which was found to be $7.53 \pm 0.96 \times 10^{12}\,\mathrm{Tm}^3$. Comparing this result to the expected value of $8 \times 10^{12}\,\mathrm{Tm}^3$, it can be seen that the calculated value is within one error value deducing that the calculated value is indeed accurate and agreeable. When calculating this average, one of the values from Table 1 was omitted due to the fact that it was a heavy outlier (as discussed in section 4.1). However, this means that there are only three flybys for data to be collected from to calculate the magnetic moment, therefore resulting in a magnetic moment that does not have much supporting evidence. This can be resolved in the future with future Juno flybys of Io giving more data for magnetic field strength, meaning there will be more magnetic moment values that can be calculated, creating a more agreeable average. On the other hand, the fact that the calculated magnetic moment is within an agreeable range to the expected value means that the use of a dipole model to portray Io's magnetic field is indeed appropriate. This helps to understand the nature of Io's induced field and how its formation is affected by Jupiter's magnetic field.

In the case of Europa, we were able to find that the magnetic dipole moment is in some ways similar to Io's. This can be attributed to the fact that both of these satellites have induced fields as well as the fact that they have internal activity which can become external and interfere with the magnetometer readings. For example, Europa has plumes or gaseous expulsions of conductive material which in this specific case can cause interference with the magnetometer readings. As we can see in Table 2, both E12 and E26 can be speculated to be close by to plume expulsion which can be attributed to interference outside of the background field and plasma currents contribution. As we can see in Figure 4, the derived magnetic moment of Europa is given by $14.89 \pm 4.71 \times 10^{11}$ Tm^3, however Europa data has no specific or generally accessible value for this. That being said, we can compare to values from simulations of these events as a reasonable comparison (as can be seen in the discussion section). In terms of future works, there is a more up to date model of the satellites around Jupiter on AMDA such that there is a set of data around shell models of certain satellites. Given that Europa would benefit the most from this as it is described as a solid core with a current conducting fluid layer, this being in between the solid core as well as the solid icy surface layer. Also, looking at more flybys, both from the Galileo mission (for which some Europa flybys we did not analyse) and the ongoing Juno mission would prove useful given that there is a large pool of data. There are also future missions such as the Europa Clipper (24) which will provide further insight and information which could support our result of the magnetic environment around Europa.

The average equatorial surface magnetic field strength found for Ganymede was $620 \pm 50\,\mathrm{nT}$, within 2 standard deviations of the $719\,\mathrm{nT}$ value given in (2), making our value agreeable. Sharp deviations from the model dipole field can be explained by magnetopause crossings for all flybys, and stemming from Galileo's position in the centre of Jupiter's current sheet for G8. Smooth deviations may be due to Ganymede's overall magnetic moment not being aligned with its rotational axis, as assumed by the model. Ganymede specifically would benefit from a more accurate model of its magnetic field, such as an intrinsic magnetic moment that points in the direction found in previous work, and an added induced field from its subsurface ocean (2). To fit the model to data, a least squares method could be employed, as used in (10), which should be more reproducible and accurate than fitting manually.

Analysis of data from all the moons could benefit from the fitting a polynomial to raw magnetometer data from outside the moons' magnetic fields, to find the background field from Jupiter at Galileo's location as was done in (2) and (10). This is likely to be a more accurate method than using models like JRM33+Con2020, which do not take into account the fact that Jupiter's field changes over time.
When reviewing Table 4 for Io, it can be seen that the average magnetic moment for Io ($7.53 \pm 0.96 \times 10^{12}\,\mathrm{Tm}^3$) is within one error of the expected value and is therefore agreeable. With the calculated average equatorial surface magnetic field strength of Ganymede being $620 \pm 50\,\mathrm{nT}$, which is within 2 standard deviations of the $719\,\mathrm{nT}$ value, it can also be deter-

Table 4. A table showing the average magnetic moments of each moon compared to their expected value. Expected values were taken from (2),(30) and (10) (from top to bottom)

Moon	Average magnetic moment(Tm^3)	Expected magnetic moment (Tm^3)
Ganymede	$1.15 \pm 0.07 \times 10^{13}$	1.31×10^{13}
Io	$7.53 \pm 0.96 \times 10^{12}$	8×10^{12}
Europa	$14.89 \pm 4.71 \times 10^{11}$	5-15 $\times 10^{11}$

mined that the magnetic moment for Ganymede which has been calculated is in fact agreeable. Both of these values being agreeable suggests that the dipole model is in fact, the most accurate way to model the magnetic fields of these two moons. The difference however, is that Ganymede has not only an induced field like Io, but it also has its own intrinsic field which needs to be taken into account throughout the calculations. Europa on the other hand, is seen to be poorly modelled by the dipole model. This is due to the fact that its induced field is hypothesised to be created by a sub-surface ocean that covers the entire moon, creating the need for a shell model to be used to accurately model Europa's magnetic field.

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Spiceypy was used to get some of the ephemeris data: https://doi.org/10.21105/joss.02050.

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APPENDIX A: DEFINITIONS OF COORDINATE SYSTEMS

System III : R is along the Jupiter to spacecraft line, positive away from Jupiter. Phi is parallel to the Jovigraphic equator (Omega x R). Theta completes the right-handed set (positive southward).

ISPRH - spherical Io-centered 'planetocentric' right-handed coordinates : R is along the satellite to spacecraft line, positive away from the satellite. Phi is parallel to the satellite's planetographic equator and positive in a right-handed sense. Theta completes the right-handed set (positive southward). The other moons have equivalent coordinate systems relative to themselves, relevant ones being: ESPRH for Europa, and GSPRH for Ganymede.

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