Modelling Io's Magnetic Field as a Dipole

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1-Introduction

Io, the third largest moon of Jupiter, is known to have a weak induced magnetic field. This is most likely due to interactions between the moon and Jupiter's much larger background magnetic field through the true mechanisms behind this are not fully understood yet. As part of my third year group project [1], my group decided to investigate the magnetic interactions between the Galilean Moons (Io, Europa, Ganymede, and Callisto) and Jupiter. Part of this project included modelling the induced field of Io as a dipole in order to quantitatively analyse its strength and behaviour. Using the equation for the dipole model (see right) and observed magnetic field data from the Galileo spacecraft (see below) we were able to determine an estimate for the dipole magnetic moment (M) of Io that was in excellent agreement with other literature.

2-Dipole Model

The induced magnetic field of Io was modelled as a dipole using the equation [4]:

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

Where B is the magnetic field magnitude observed - typically measured in Nanoteslas [nT]; r is the radial distance from the moon to the observer measured in metres [m]; θ the angle between the position vector **r** and the induced field direction and M is the dipole magnetic moment which we are trying to find.

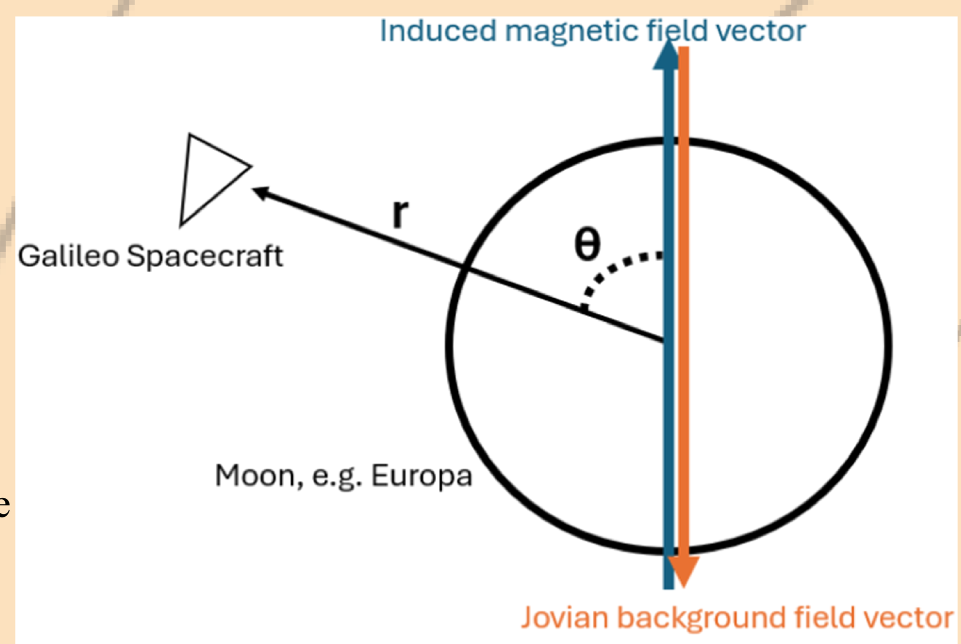

Figure 1 - Schematic demonstrating the direction of the position vector **r** in relation to the induced and background magnetic fields of the moon in order to clearly define the parameter θ in the dipole model equation. Figure taken from my 3rd Year Group Project Report [1]

3-Data

Measurements of the observed local magnetic field components were recorded by the Galileo Spacecraft's magnetometer as it underwent close flybys of Io during it's mission around Jupiter in the late 1990s and early 2000s. This data was provided to us for our investigation by AMDA [2] along with ephemeris and universal time data in order to calculate the position of the spacecraft relative to Io at any given time. This is where the data for B, r and θ came from in order to calculate M in the dipole equation (see top right).

Figure 2 - The Galileo Spacecraft

The data for the background magnetic field from Jupiter (that needs to be subtracted to remove noise) was taken from the Jovian Magnetic Field Model "JRM33+Con2020" [3] which was also provided by AMDA.

4-Method

The start and end times of a close flyby of Io by the Galileo Spacecraft were determined first and the raw measurements of the components of the local magnetic field were recorded. The background field from Jupiter was then subtracted from these measurements to remove noise from the data and so that only contributions from Io's field should remain. This was done by estimating the vectors of Jupiter's background field using a Jovian Magnetic Field Model (see data section above).

Python code was developed to find θ by finding the scalar product of the position vector of the spacecraft relative to the moon (**r**) and the induced magnetic field vector. (See schematic top right). Once θ had been determined, the observed magnetic field magnitude could be divided by the $(1+\cos^2(\theta))^{1/2}$ term to obtain:

$$B_{eq} = Mr^{-3}$$

Where B_{eq} is the equatorial magnetic field (dependence on θ has been removed). A plot of B_{eq} vs r^{-3} can then be made where the slope of the line of best fit can be taken as an estimate for M. Before this however we first had to estimate the area of effect for Io's magnetic field. This is because we observed the linear relationship between B_{eq} and r^{-3} broke down for high r. The area of effect was estimated by plotting B_{eq} against r and seeing at what value of r does B_{eq} drop off. Once we had an estimate for the area of effect the plot of B_{eq} vs r^{-3} can be redone only including r values within the area of effect to get an estimate for M.

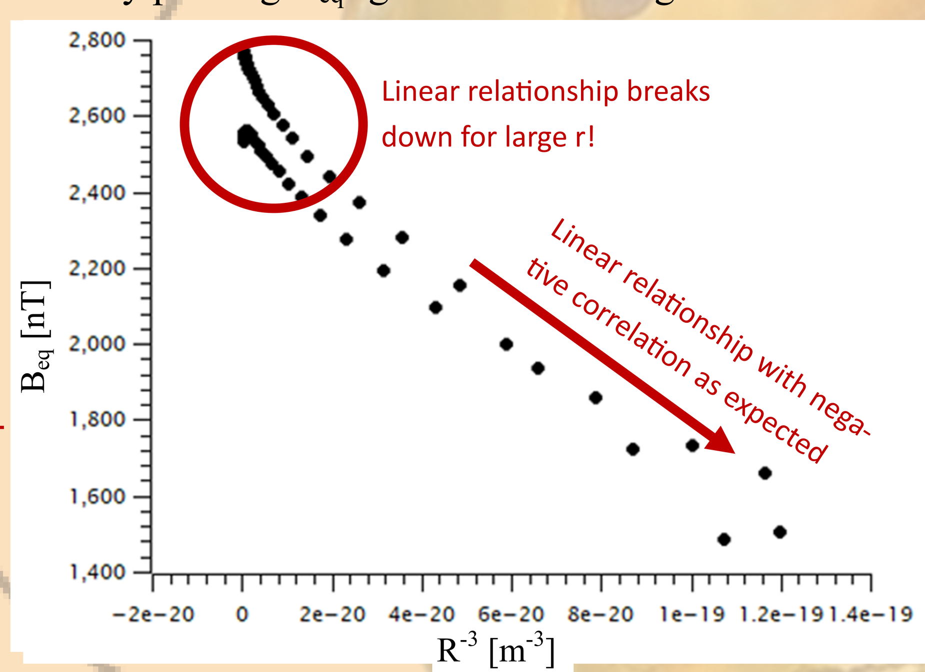

Figure 3 - B_{eq} vs r^{-3} for the Galileo Spacecraft flyby of Io "I27". The expected linear relationship breaks down for large r due to these values being outside the are of effect of the moon's magnetic field.

5-Results & Discussion

The area of effect of Io's magnetic field was found using the method discussed (see left) for the flyby "I27" which occurred on 22/02/2000. The results are shown in Figure 4 below:

The area of effect was estimated to be 6×10^6 m. By omitting any values of r greater than this and plotting B_{eq} vs r^{-3} as discussed in the method section will allow us to find an estimate for M by finding the slope of a linear fit. The results for this linear fit are shown in Figure 5. This procedure was repeated for 2 other flybys and the values of M obtained for all four are presented in Table 1.

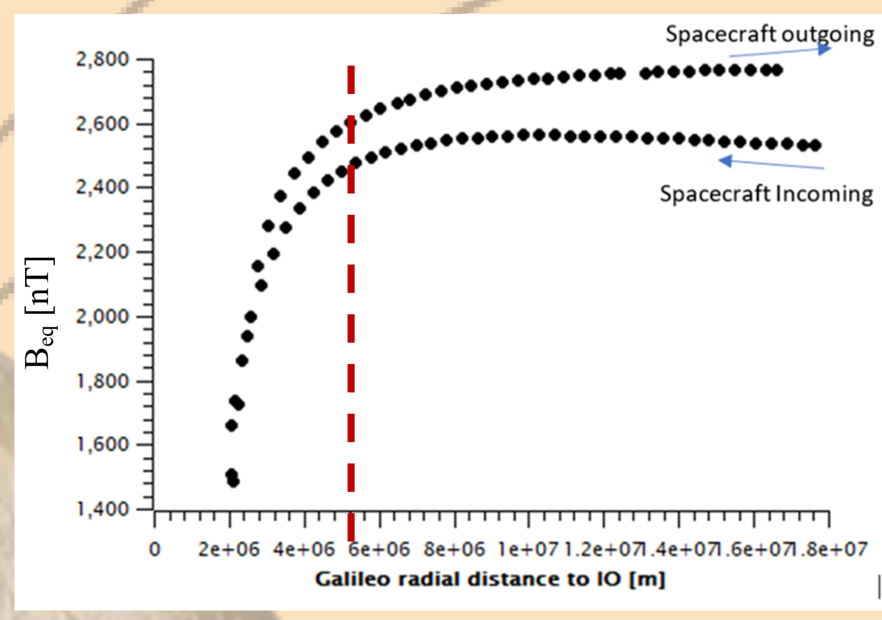

Figure 4 - B_{eq} against r to estimate the area of effect of Io's magnetic field. At $r = 6\times10^6$ m is when the field begins to significantly drop off.

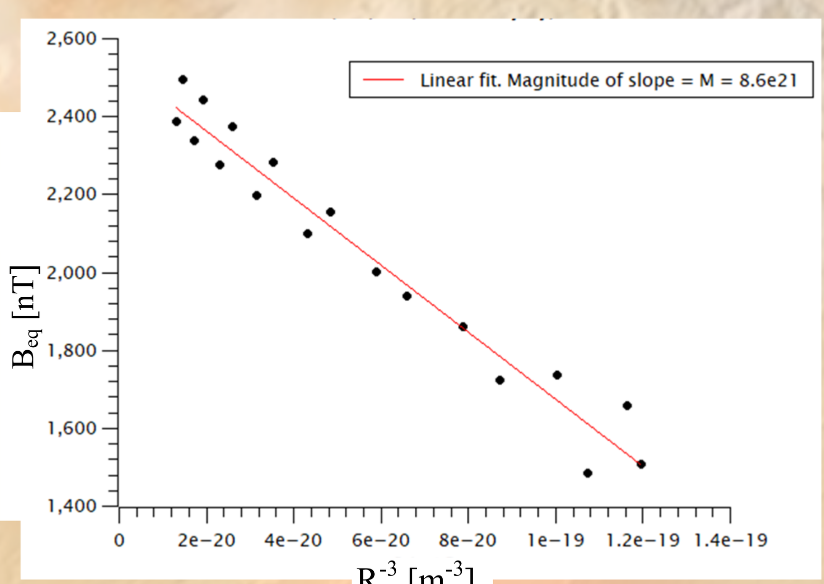

Figure 5 - B_{eq} vs r^{-3} for the Galileo Spacecraft flyby of Io "I27". With values of r > area of effect omitted. Linear fit to estimate value of M.

Flyby Date	Magnetic Moment (M) [Tm^3]
07/12/1995	$7.6\pm2 \times10^{12}$
11/10/1999	$6.4\pm0.5 \times10^{12}$
22/02/2000	$8.6\pm0.4 \times10^{12}$
16/10/2001*	$3.0\pm0.3 \times10^{12}$ *
AVERAGE:	$\mathbf{7.53\pm0.96 \times10^{12}}$

Table 1 - Obtained values of the magnetic dipole moment (M) for 3 different flybys of Io by the Galileo Spacecraft. *Note 4th flyby was omitted from the average due it being a clear outlier.

Our average value of M obtained was $7.53\pm0.96 \times10^{12}$. This was after omitting the fourth flyby from our calculation as we discovered the spacecraft actually flew through a volcanic plume during this flyby and was damaged which could be why this value is a big outlier. An expected value of M from other literature is $\sim 8 \times10^{12}$ nT [5] which is in excellent agreement with our obtained value. This suggests that the dipole model is a good fit to estimate the behaviour of Io's magnetic field.

6-Conclusions

Our dipole model is a good estimate for the nature of Io's magnetic field. This is because estimating the field as a dipole using the dipole field equation successfully yields a value of the dipole magnetic moment M that is in excellent agreement with the expected value. Understanding the nature of Io's magnetic field is important as it helps us understand how it may be induced through interactions with Jupiter. Further improvements can be made to this investigation such as using a better model to estimate Jupiter's background field and using more than just 3 flybys for our estimate for M. Future research using more up to date observations such as those made by the Juno probe can also be used to further improve our understanding of the nature of Io's magnetic field.

Acknowledgements

[1] With thanks to Ewan Gregg, Joe Lane, Jacob Perry & George Poole for their contributions towards the 3rd year group project research and final report and our supervisor Sarah Badman.

[2] Data analysis was performed with the AMDA science analysis system provided by the Centre de Donn´ees de la Physique des Plasmas (CDPP) supported by CNRS, CNES, Observatoire de Paris and Universit´e Paul Sabatier, Toulouse.

[3] Jupiter background field models: Connerney et al., 2022 for the internal field (JRM33) and Connerney et al.,2020 for the external field (Con2020).

[4] Dipole Field Equation from Kivelson, M. G. and Russell, C. T. in "Introduction to Space Physics" (Cambridge Univ. Press, 1995).

[5] Expected Value for M from Kivelson, M. G., K. K. Khurana, R. J. Walker, C. T. Russell, J. A. Linker, D. J. Southwood, and C. Polanskey, A Magnetic Signature at Io: Initial Report from the Galileo Magnetometer, Science 273, 5273, 1996b