MAGNETODISC OF JOVIAN MAGNETOSPHERE

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TERM PAPER

Abstract

This paper gives a brief report about Jupiter's magnetodisc and its current system.The formation of magnetodiscs are caused by outward stretching of field lines loaded with plasma and the motion of this disc gives us knowledge about low-frequency wave generation. Structure, nature and periodicities of the current sheets are discussed with spacecraft flyby data. The approach for understanding the magnetodiscs current system has been taken with different models suggested by previous researches and their data.

Keywords: *Magnetodisc ;Magnetosphere ;Current-Sheet*

1 Introduction

The largest planet in our solar system is Jupiter, with its huge body, it also corresponds to the largest magnetosphere among the other planets, extending its magnetosphere up to Saturns orbit and the strongest magnetic field (with its magnetic moment is 2×10^4 times that of the earth). The Jovian magnetosphere has three main parts, i.e the inner magnetosphere up to $10R_J$ (radii of Jupiter), $10R_J$ to $30R_J$ is the middle magnetosphere, beyond this is the outer magnetosphere from $50R_J$ to $150R_J$ bounded by the magnetopause. Giant planets like Jupiter have rapidly rotating magnetosphere with angular velocity $(\omega_J) of 1.76\times10^{-4}s^{-1}$, such rotation causes an outward stretching of magnetic field lines loaded with plasma from the planet making a disc-like structure (*magnetodisc*)(see Fig 1)***(R. A.Kislova et al., 2012).*** The magnetodisc concentrated with hot plasma rotates at a rate which varies with the radial distance of the planet, Pioneer 10 satellite with its measurements of particle flow and magnetic fields was the first to detect the magnetodisc in Jupiters magnetosphere. The Pioneer 10 and 11s magnetic field measurements revealed the existence of a current sheet (*thickness* $\approx 2R_J$) which carries eastward current, in the order of $10^{-2}Am^{-1}$ and hot plasma (T > 1keV). The current sheet being warped azimuthally and parallel to the magnetic dipole equator ***(Goertz, 1979)***.

Since the disk contains hot plasma and co-rotates with radial distance, ***Kane et al. (1999)*** with the help of Energetic Particle Detector (**EPD**) on the Galileo spacecraft showed hot ions in the neutral sheet region of the magnetodisc to be a three-species κ distribution function. The nature of the distribution functions tells us about important quantities like pressure, density, composition and temperature of hot ions in the Jovian system (***Kane et al., 1999***), the ion distribution function. We would be mainly discussing the middle and outer magnetospheres in this paper where the magnetodisc is concentrated. Later, the nature, structure and about the periodicities of the current sheet present in the Jovian magnetosphere with the help of some magnetohydrodynamic (**MHD**) models of the Jovian magnetodisc is also discussed.

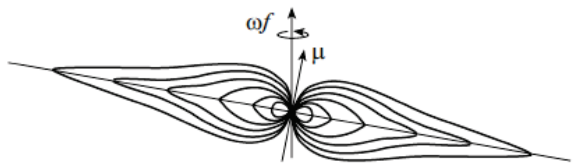

Figure 1: *Magnetic field lines of the Jovian magnetodisc in the meridional cross section detected by Pioneer 10.*

2 MAGNETODISC

2.1 Formation of the Magnetodisc

Magnetodiscs are the special features of Giant rotating planets like Jupiter, they are large current sheets which are filled with plasmas from the surrounding satellites of Jupiters system. The Magnetic field lines of Jupiter are stretched along the equator across the day and night sides which make radially extended azimuthal current-flow in day and night side, these current-flowing regions in the presence of dense plasma near the equatorial region are referred as the magnetodisc. Under the influence of the dominating magnetic field of the planet, currents are generated, with rotating magnetized plasmas in the magnetosphere forming the magnetodisc region ***Kivelson***, 2014. The current flow in the magnetodisc of Jupiter shown in (Fig 2) with an orange line which starts from the middle magnetosphere ($\approx$ 20R$_J$)extending to the outer magnetosphere (<50R$_J$). The current flow in these orange regions are radially outwards and the field-aligned are matched to the ionosphere, resulting in partial co-rotation of the plasma due to the currents. The magnetodisc moves from north to south with planets rotation such as in Jupiter and Saturn and is not rigid.In Jupiter, the centripetal force is too large because of high amounts of plasma and rapid rotation of the planet, making the plasma pressure inconsistent, making azimuthal currents more significant in all local time.

An azimuthal current reduces the radius of curvature (R$_C$) by stretching the field lines near the equator due to pressure gradients or inertia of the rotating plasma; changing the radius of curvature gives a force balance equation as:

$$\nabla.(\mathbf{P} + \frac{\mathbf{BB}}{2\mu_o}) - \hat{n}\frac{B^2}{\mu_o R_C} + \rho\mathbf{u}.\nabla\mathbf{u} = 0 \tag{1}$$

Here $\mathbf{P}$ denotes the pressure, $\mathbf{B}$ the magnetic field, $\hat{n}$ is the unit vector normal to the field, ρ the mass density and $\mathbf{u}$ is the flow velocity in polar coordinates. Other than the curvature force, all the other forces near the equator are normally outward, increasing the inward curvature force as well to balance the other forces, making the field lines to stretch and R_C to decrease ***(Kivelson,*** 2016).

2.2 Dynamics of the Magnetodisc

There have been several spacecraft near the equator which have observed plasma sheets passing up and down in near $\approx$ 10 hours see (Fig 3), here the magnetometer data of the voyager 1 is shown as it moved away from the Jovian equator (*Khurana and Schwarzl*, 2005). As of date, in all the magnetospheres, plasma sheet does not stay rigid nor fixed in the magnetotail. Its position and

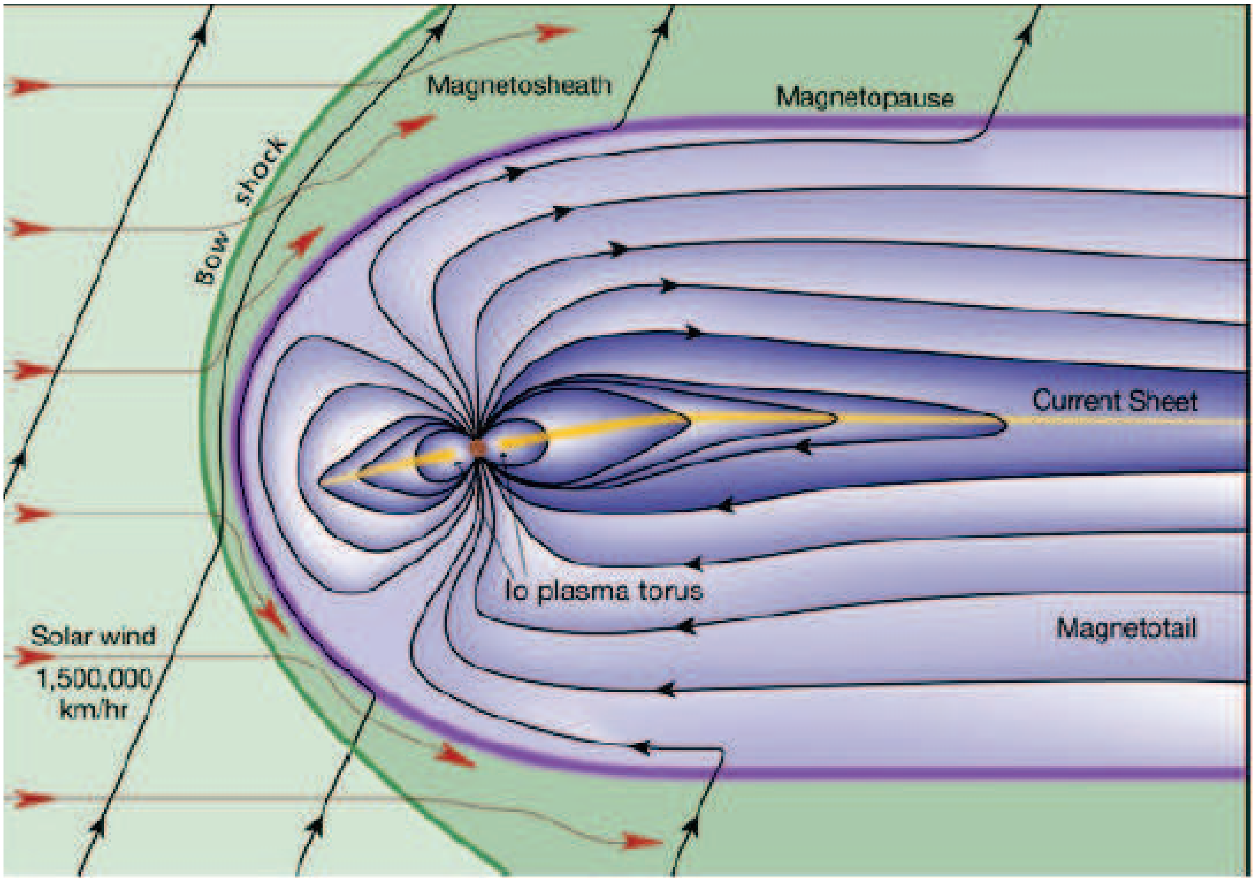

Figure 2: *Shows the Jovian magnetosphere, field lines in black, solar wind flow in the direction of the red arrows. Plasma dominated in the internal magnetosphere is in purple and by the solar wind is in green. The region with orange colour in which the current is contained that flows azimuthally and makes the radially stretching of the field* ***(Bagenal and Bartlett, 2013)***.

movements are imposed by the tilt of the planetary dipole moment. The rotation axis of Jupiter is tilted by 3^o to its orbit and the dipole is tilted 10^o with its rotational axis. Therefore, when the dipole axis rotates with its spin axis it causes the magnetic equator to tilt making north-south displacement on a warped plasma sheet (the plasma sheet lies near the magnetic equator where the centre of the sheet bows northward when magnetic north tilts towards the sun, and southward when it tilts away from the sun) (***Kivelson***, 2016).

The radial component here is the dominant component in magnetic field which is positive in the north of equator and opposite in the south. This timely sign change of the radial component of the magnetic field reveals the plasma sheet moves up and down over the spacecraft as shown in (Fig 3). The longitudes at which the radial components change are strongly dependent on the distance from Jupiter and shown in (Fig 3) by ***Khurana and Schwarzl***. They concluded that there were two processes to phase delay. First being the internal magnetic field, which is strong near the planet due to which the plasma sheet is very close to the magnetic equator and the displacement of the plasma sheet causes signal carried by **MHD** waves that go down the tail and impose north-south movement of the plasma with a delay that increases with distance. The second is when the plasma moves out, it conserves angular momentum which decreases the angular velocity causing

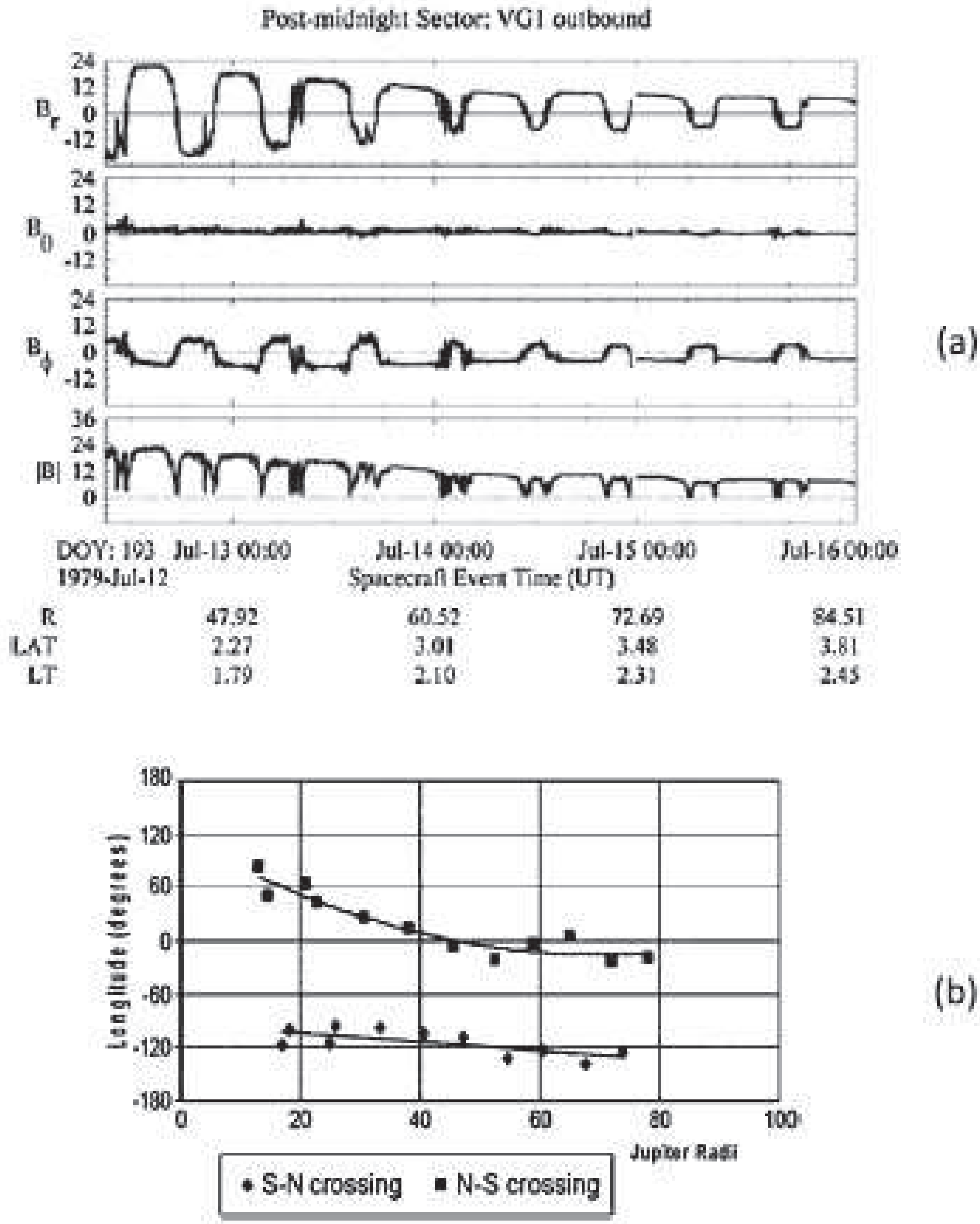

Figure 3: *(a) shows the magnetometer data of voyager 1 outbound in the Jovian magnetotail.(b) shows the plot between the longitudinal crossing of current sheet in degree vs. radial distance for N-S (square) and S-N (diamonds) crossing* (**Khurana and Schwarlz,** 2005).

a "co-rotational lag" that twists the magnetic field out of the meridian plane taking place beyond $20R_J$. This produces some additional lag in crossing time and these two processes produce a delay of Alfven speed $\approx$ 780 km/s shown in (Fig 3).

2.3 Waves in Jovian Magnetodisc

Generation of low-frequency waves like ion cyclotron waves and mirror mode waves are observed in Jupiter's magnetodisc where mass loading occurs. These waves are important in context as they tell us about the local composition of plasmas and where ion pickups are situated. The ion pickup rate is largest near Io in Jupiter's system, nearly about $\approx$ 500-1000 kgs^{-1} of neutral gas becomes ionized near Io due to photoionization, charge exchange and impact of thermal background plasma with electrons (***Achilleos et al.***, 2015). Io orbit around $\approx$ 17kms^{-1} and the plasma rotating around Jupiter with an azimuthal speed of $\approx$ 74kms^{-1}, therefore the plasma moves around $\approx$ 57kms^{-1} relative to the ionosphere of Io. This makes the new ions suffer an outward electric field with the relative velocity of $\approx$ 57kms^{-1} with a southward magnetic field of $\approx$ 2000nT. This makes the new ions go in cycloidal trajectory in space, drifting and gyrating along the magnetic field. This kind of motion is circular with the centre and speed of gyration fixed, causing the ions to form a ring-like distribution. The Ion cyclotron waves and mirror modes are made with the ring-distribution introducing an effective temperature anisotropy into the plasma.

3 MAGNETODISC CURRENT SHEET

3.1 Nature of the magnetodisc current sheet

The local currents which flow eastward around Jupiter are confined to a current sheet. The sheet causes the field lines to be extended radially confining energetic particles to it. Due to azimuthal stress on plasma, the field lines are bent against the rotation of planet which delays the current sheet. Frequency of the current sheet is caused by the consequence of the period of rotation of the planet.

Planetary dipoles rotational phase determines the outer magnetospheric disc plasma, which rotates with the planet. In the middle magnetosphere of the extended model (Fig 4), the plasma sheet is thinner. This causes the field lines to shape more disc like in this case. The cold plasma pressure in these models decreases along field lines as,

$$P = P_o exp\left\{\frac{\rho^2 - \rho_o^2}{2l^2}\right\} \tag{2}$$

Here, ρ_o is the cylindrical radial distance from the equatorial point of the field line and 'l' the pressure in the scale of length where $l^2 = \frac{2K_BT}{m_i\omega^2}$.

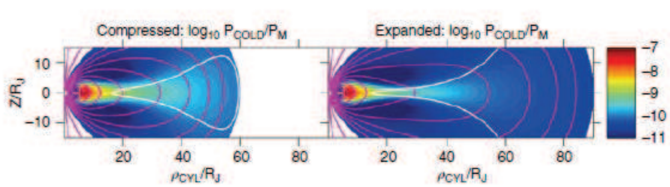

Figure 4: *Computed pressure of cold plasma of the Jovian magnetodisc with equatorial radii of $60R_J$and $90R_J$ (**Achilleos**, 2018).*

For a disc like field, the points on the field line with distance ($\rho_o - l$) are present at a smaller vertical distance from the equator, leading to a thinner plasma sheet (***Achilleos***, 2018).

3.2 Structure of the magnetodisc current sheet

The Jovian magnetodisc, that is the current sheet, lies between the plasmas which have similar properties. The magnetic field of the Jovian system is bipolar, close to its distance but the radial distance becomes less about $24R_J$ and the field becomes more like a disc. The Magnetic field reverses in the current sheet with the field varying linear, the current sheet also contains a variable irregular field along the normal. When their duration are compared with the current sheet crossings, these field reversing structures looks smaller. Similar structures are seen in the Earth's magnetopause and outer planets and are similar in magnetopause and magnetodisc currents with similar consequences (***C.T. Russell et al.***, 1999).

3.3 Periodicities of the Jovian magnetosphere

Flux and magnetic field periodicities in the Jovian magnetosphere are observed, one of the models is the magnetodisc type where the particles are distributed in a thin disc. The up and down motion of the disc gives the observed periodicities ***(J.F Carbary,*** 1980).

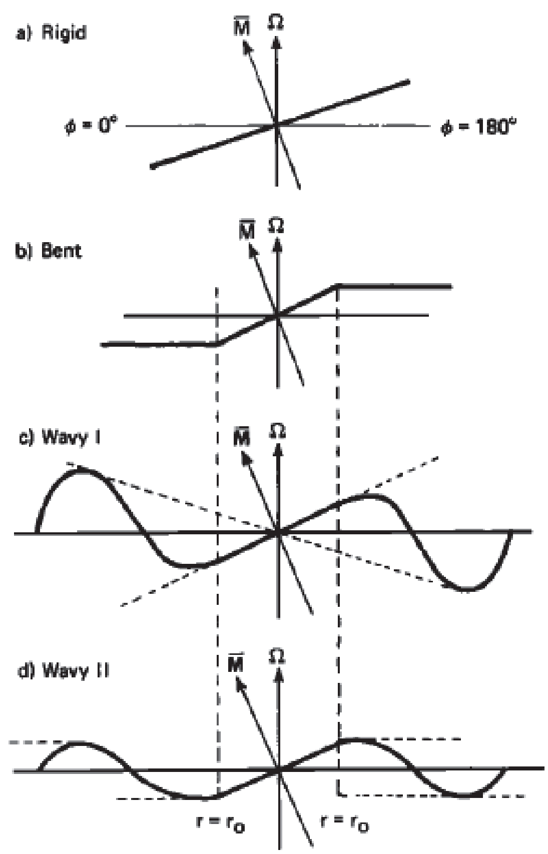

Figure 5: *Different Magnetodisc models, here M gives the magnetic axis and Ω the spin axis (**J.F Carbary**, 1980).*

There are three main magnetodisc models,

1. Rigid magnetodisc model, here particles are concentrated in the dipole magnetic equatorial plane.
2. Warp or bent magnetodisc model, the disc bends parallel due to centrifugal forces present in the outer magnetosphere to the spin equatorial plane.
3. Wavy magnetodisc model, a wave is generated in the disc due to the wobbling of the inner dipole fields.

4 Discussion and Conclusion

So far we have seen that magnetodiscs are large current sheets surrounding planets like Jupiter. Most of the works on the current sheet assume that the plasma in the outer magnetosphere co-rotates rigidly with the planet. From various models, it is seen that the plasma is concentrated near the equatorial plane and the plasma density decreases rapidly than its pressure which implies that the temperature increases with distance (***Goertz***, 1979). There are still some phenomena that are crucial to understanding like Jupiter's magnetodiscs north-south movement, as the planet rotates. The field lines are stretched at the equator distorting the field, implying the presence of a radial azimuthal current flow this causes the current sheet to confine energetic particles. The generation of low-frequency waves makes ions in the disc gyrate in space and move in a cycloidal path along the field lines. There are still some interesting questions for example how does the plasma get into the magnetodisc from various sources *i.e* the radial transport of plasma?, there are reconnection events occurring where mass is lost from the magnetosphere and one might ask how is the reconnection happening and in magnetodiscs, there are structures which are asymmetric in local time. These asymmetries are found in the thickness, location and field structures, that still haven't been understood (***Kivelson***, 2016) and still remains an inactive area of research.

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