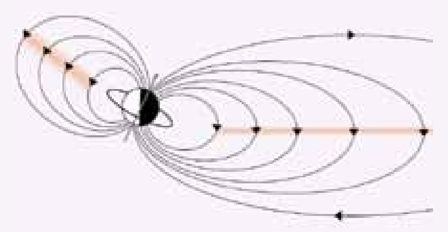
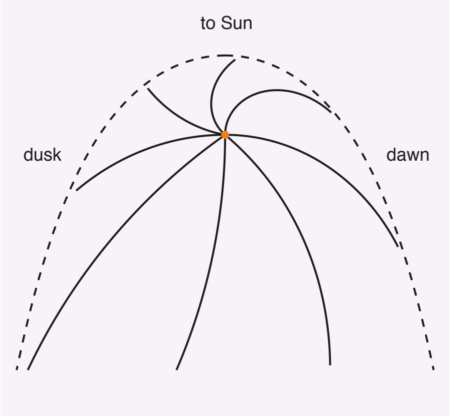
Cassini tracks Saturn's equatorial current sheet

Carley J Martin and **Christopher S Arridge** discuss the dynamics of the thin current sheet at Saturn's equator, a presentation that won a Rishbeth Prize at NAM in 2016.



1 (Above) Saturn's magnetosphere as seen from the side. The current sheet is shown in orange, surrounded by a stretched outwards field in the radial direction. Also apparent is the hinging of the dayside and nightside current sheet to form a bowl shape.



2 (Right) The azimuthal magnetic field at Saturn, seen from above. The dawn section of the magnetosphere shows a "swept-back" field arrangement where the field begins to lag behind the rotation rate. This lag arises because the plasma in the equatorial region is transported outwards and slows down (sub-corotating) to conserve angular momentum. As the magnetic field lines are frozen into the plasma, the lag affects the magnetic field lines as well. Alternatively, confinement by the solar wind shows that the dusk section of the magnetosphere frequently has swept forwards field lines. The direction of the sweeping of the field lines is in reference to the direction of corotation that occurs anti-clockwise in this figure, so a swept backwards field is swept in the clockwise direction. This same process also occurs at Jupiter.

The Cassini spacecraft has been in orbit around Saturn since 2004. Before this mission, Saturn had only been visited by three other spacecraft on brief fly-bys. Their three trajectories limited any spatial analysis; detailed investigation of the magnetic field was only possible with the arrival of Cassini. In 1979, Pioneer 11 was the first spacecraft to investigate Saturn's magnetic field and also discovered the smaller minor moon Epimetheius and Saturn's F ring. The fly-by confirmed the idea that the magnetic field is similar to Jupiter's, which Pioneer 11 had encountered in 1974 and which Pioneer 10 had measured in the previous year (Smith *et al.* 1980). Saturn was also visited by both Voyager missions, in 1980 and 1981. Voyager 1 gave a much needed insight into Titan's intriguing environment as well as the first high-definition images of Saturn (Smith *et al.* 1981, Lindall *et al.* 1983). The second Voyager spacecraft aided the discovery that Saturn's rings are active and constantly changing (Smith *et al.* 1982). Voyager 2 went on to visit both ice giants, Uranus and Neptune; both Voyager probes are still in use today as they reach the outermost parts of the solar system and beyond. Since orbit insertion, the Cassini–Huygens mission has given an in-depth and unprecedented insight into Saturn and Titan and their planetary environments, including their plasma and magnetic environments.

A planetary magnetosphere is a large cavity in the solar wind in which plasma motions are controlled by a planet's magnetic field. This shields the planet and any inner moons from the solar wind, which is a supersonic flow of plasma from the Sun. Saturn's magnetosphere is comparable to Earth's much smaller magnetosphere, which protects everyone on Earth from this particle flow and participates in the production of the aurora.

> **"Like Jupiter, Saturn's magnetosphere is largely controlled by the planet's rotation"**

Plasma movement

At Earth, the movement of plasma and magnetic flux is controlled primarily by the interaction between the solar wind and magnetosphere: solar wind and planetary magnetic field lines are reconnected on the dayside and move to the nightside of Earth, causing a large-scale movement of magnetic flux over the polar cap and back around to the dayside, a process named the Dungey cycle. At the other extreme, at Jupiter, the plasma is controlled mainly by the planet's fast rotation rate. This rotation is carried out to the large amount of plasma within the magnetosphere, which originates from the volcanic moon Io; the frozen-in magnetic field lines and the whole magnetosphere revolve with the planet once every 10 hours.

Saturn's magnetosphere is often seen as a mid-point between these two. Like Jupiter, Saturn's magnetosphere is largely controlled by the rotation of the planet. However, Saturn's magnetosphere is much smaller than that of Jupiter. The magnetopause at Saturn – the boundary between plasma controlled by the solar wind magnetic field and that controlled by Saturn's magnetospheric magnetic field – is located around 1.3 million km sunwards from Saturn (Achilleos *et al.* 2008), whereas Jupiter's can be found upwards of 3.4 million km away (Huddleston *et al.* 1998). A schematic of the magnetosphere of Saturn can be found in figure 1. Saturn's magnetosphere also contains a much smaller population of plasma than Jupiter, causing Saturn to be influenced by the solar wind more than Jupiter, forming a Dungey-like cycle similar to Earth but over much larger timescales (Cowley *et al.* 2003, 2004).

Equatorial current sheets

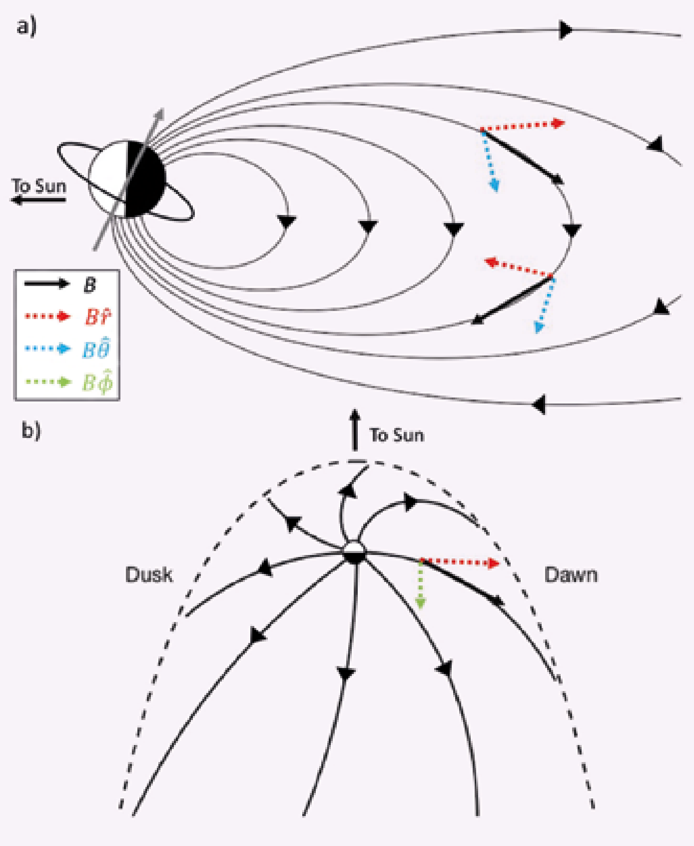
Various mechanical forces act on the magnetospheric plasma, such as pressure gradients, pressure anisotropy, gravity and the centrifugal force. In a steady state the net force must be balanced by magnetic forces. This requires the presence of a current sheet; if the currents are sufficiently strong, the field will be stretched out into an elongated disc shape. The centrifugal force is imparted on to the plasma via field-aligned currents that accelerate the plasma to move approximately with the planetary ionosphere. This shape is visible in figure 2, where the field lines are stretched on both sides of the planet.

The magnetic field data are often analysed in spherical polar coordinates $\mathbf{B}=(\mathbf{B}_r,\mathbf{B}_\theta,\mathbf{B}_\phi)$. The field is strongly positive in the radial direction (away from the planet) above the equator and negative radially below the equator. When including the sweptback field mentioned above, an azimuthal component to the field is included, one which is negative above the equator and positive below when swept backwards, so that the magnetic signatures in data appear in anti-phase in the two components. Figure 3 resolves the magnetic field components in $\hat{r}$, $\hat{\theta}$ and $\hat{\phi}$, showing how $\mathbf{B}_r$ changes from positive above the equator to negative below the equator. Additionally, figure 3b shows the components above the equator from above. In the diagram, we see that $\mathbf{B}_r$ is still positive but $\mathbf{B}_\phi$ is negative above the equator. If we then travel below the equator, the magnetic field direction is reversed so that $\mathbf{B}_r$ is now negative and $\mathbf{B}_\phi$ is positive. This causes an anti-phase magnetic signature between the two components when the spacecraft passes from above to below the equator, and vice versa.

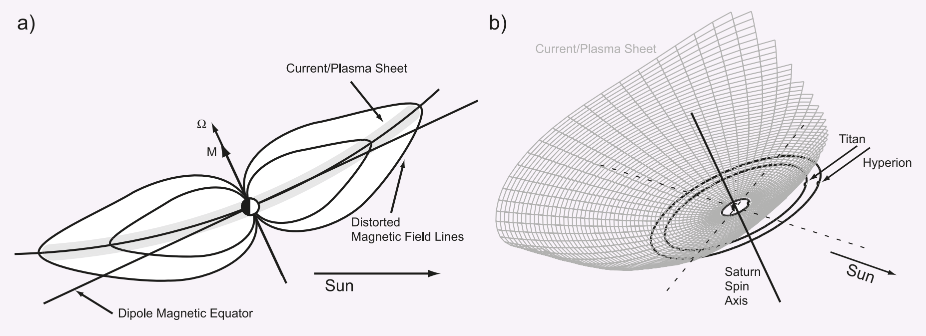
Additionally, also evident is the fact that $\mathbf{B}_\theta$ is generally negative in all areas as the dipole field of Saturn is directed from "geographic" north to south. Periods where $\mathbf{B}_\theta$ becomes negative can be a signature of magnetic reconnection in the magnetosphere where the orientation of the field means that Cassini will be tailward of an X-line.

The two regimes of oppositely directed magnetic flux above and below the equator are separated by a current sheet near the equator (orange area in figure 1). The forces that act on the plasma and are associated with the presence of the current sheet act in all local time sectors, and so the current sheet exists in all sectors, forming a disc-like torus.

This process at Jupiter, in combination with a large plasma population from Io, results in a very large disc of plasma all around Jupiter, which hinders any influence from the solar wind as mentioned above. At Saturn, however, the content of the current sheet is much less, but is still seen in all local time sectors when in an enlarged magnetosphere. Conversely, at a time of compression of the magnetosphere, the noon section of the current sheet can be disrupted by the smaller magnetopause distance.



3 (a) Side view of Saturn's magnetosphere showing the B_θ and B_r components of the field. Above the current sheet we find a positive radial component, below a negative component with a steady positive B_θ. (b) View from above Saturn showing the field above the current sheet: a positive radial component and a negative B_ϕ. The opposite is found in the southern magnetic hemisphere, where the magnetic field is directed towards the planet, with arrows opposite to those shown. Then, beneath the current sheet, we have negative B_r and positive B_ϕ.

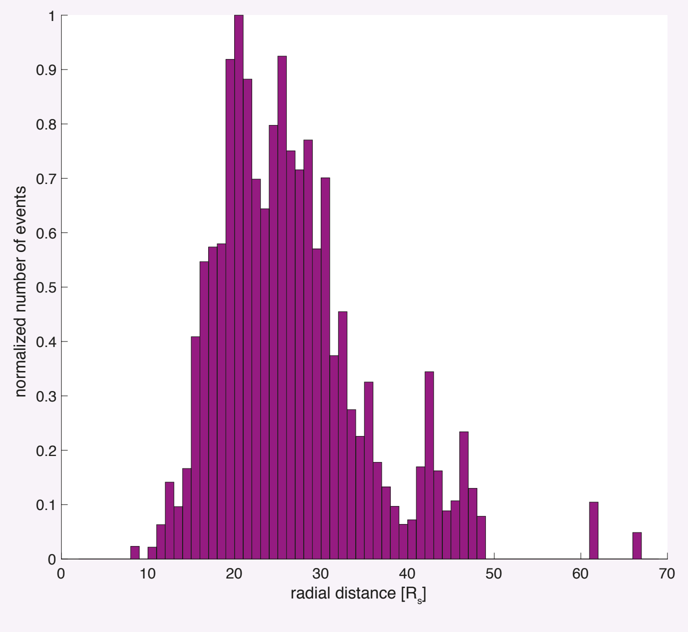


4 (a) Side view of the bowl shape of Saturn's current sheet, emphasizing the distance from the dipole magnetic equator. (b) 3D view of the distorted current sheet in the bowl shape. (Both Arridge *et al.* 2008)

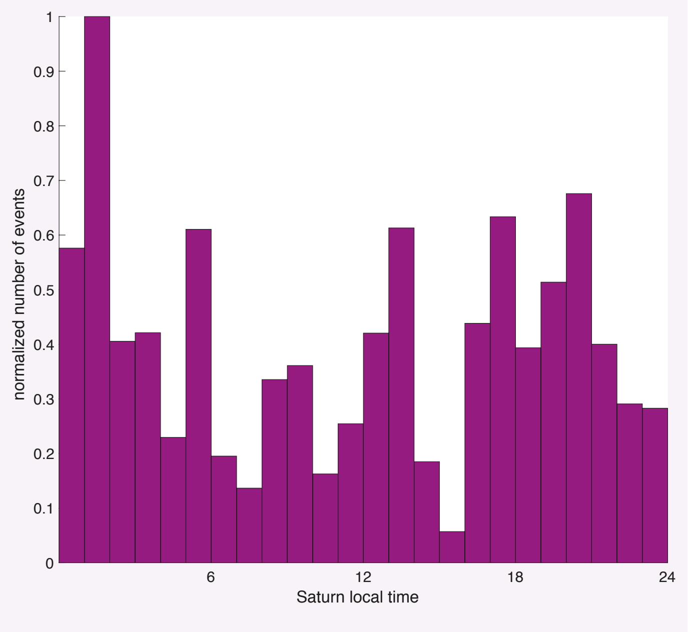
Current sheet dynamics

This equatorial current sheet does not always lie directly on the equator and it is not always planar; many factors cause the sheet to be disturbed from its equilibrium position. Solar wind influence and seasonal motion of Saturn's rotational equator with respect to the solar wind serve to push the current sheet up off the equator into a bowl shape during northern winter time, and down under the equator in summer time (Arridge *et al.* 2008). Saturn is the only gas giant where this phenomenon has been observed so far. Figure 4 shows a 3D representation of this bowl shape at northern winter time (from Arridge *et al.* 2008) in which the orbits of moons Titan and Hyperion are clearly shown to be below the current sheet. This observation leads to the view that even though they lie at the equator, the outer moons of Saturn do not always encounter the current sheet. A different arrangement occurs at Jupiter: the current sheet is aligned with the magnetic equator in the inner magnetosphere, bends towards the rotational equator, which is tilted at 10° from the magnetic axis, then becomes parallel to the solar wind in the outer magnetosphere, creating an S-shaped current sheet (Behannon *et al.* 1981).

As well as the bowl shape, a wave with a period of roughly 10.7 hours is also present at Saturn's equator. At Jupiter, the offset of the magnetic axis from the rotational axis by 10° means that every 10 hours (Jupiter's rotation rate) the current sheet will move



5 Distribution of aperiodic waves in each radial distance sector, $1\,R_S = 58\,232$ km. Distribution shows a peak at $20\,R_S$ and a tail off towards $50\,R_S$.



6 Distribution of aperiodic waves in each Saturn local time sector, where 0 SLT is midnight on the planet, and 12 SLT is the meridian directly beneath the Sun. The distribution shows a steady number of events occuring in all local times with a small majority occurring in the evening and night.

from being below the rotational equator to being above it, causing a 10-hour period wave in magnetometer data. At Saturn, the magnetic axis is offset by less than half a degree from the rotational axis (Smith *et al.* 1980). Hence the source of this rotational rate flapping of Saturn's current sheet is still a hot topic. However, it can be seen that the wave at Saturn has a much lower amplitude and is mainly visible as a movement towards and away from Cassini, rather than a pass through the current sheet every 10.7 hours. These large planetary period waves are seen using Cassini's on-board magnetometer (MAG; Dougherty *et al.* 2004).

"The study of these smaller and unpredictable waves provides a key insight"

Additionally, smaller aperiodic waves are also present; Arridge *et al.* (2007) use these waves to calculate stress balance in the magnetosphere, although the origin of the waves is still unknown. These short-period, non-repeating waves occur at all local times and all radial distances beyond $10\,R_S$ (Saturn radius, 60 268 km). Figure 5 shows this distribution, with the waves appearing at $10\,R_S$ and tailing off towards $50\,R_S$ and with the majority between 20 and $30\,R_S$. In Saturn local time, the distribution of waves peaks in the dusk and night sectors, with a steady number occurring at all local times, as shown in figure 6. Local time denotes the position of the Sun with regards to the planet's surface where 12 SLT is the meridian where the Sun is directly overhead. Both histograms are normalized to the dwell time of Cassini in each bin so that trajectory bias and areas where Cassini spent a lot of time, but found no encounters, are accounted for.

These waves usually last between a few minutes and half an hour, and appear as an anti-phase single wave pulse in the radial and azimuthal components of the magnetic field, where Cassini is embedded in one lobe of the magnetosphere; then the current sheet moves over Cassini so that the spacecraft samples the opposing lobe briefly and back again. Figure 7 shows an example of this anti-phase relationship in the radial and azimuthal components, showing that the magnetic field in the area of this wave is swept backwards. As well as the main components, two hodograms are displayed to the right of the graph, presenting the relationship between two magnetic field components. The top hodogram shows a clear "swept-back" signature where the radial and azimuthal components decrease together to zero with opposing sign, and conversely increase from zero with opposing sign to the other side. The second hodogram shows the relationship between radial and polar coordinates; it shows that $\mathbf{B}_\theta$ has no visible relationship with the radial component.

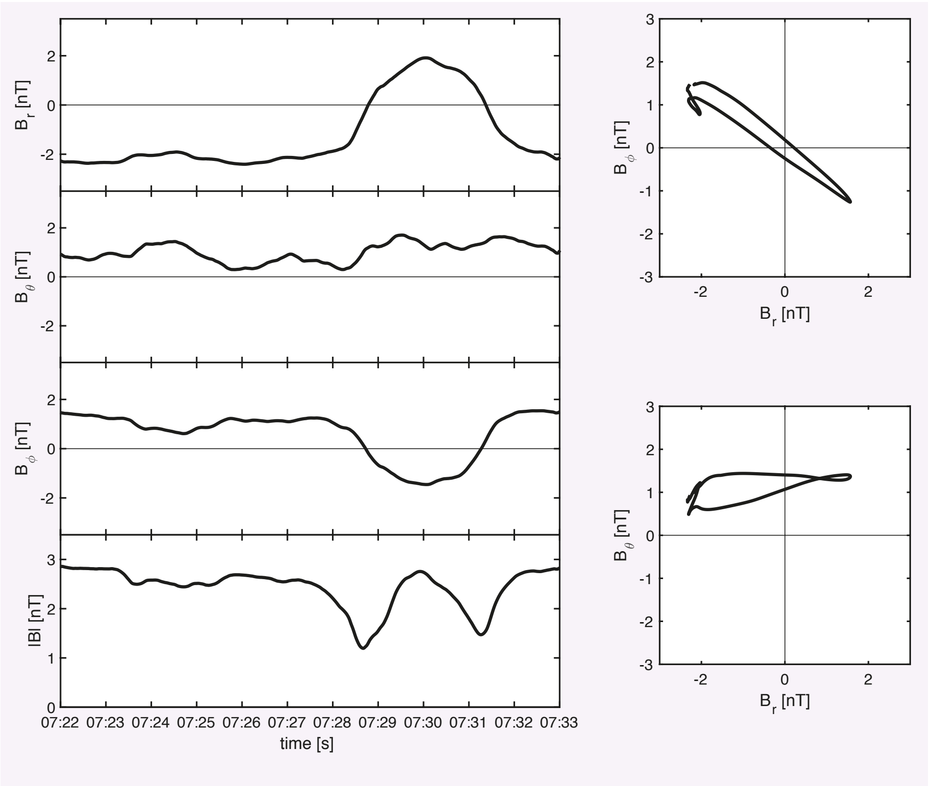
Aperiodic waves do not always appear as a single, perfectly anti-phase signature in MAG data. The variability of the signatures is most commonly associated with the surrounding magnetic field. A large number of signatures are offset slightly in the radial or azimuthal component. This shifting means that a guide field in either component is causing the components of the magnetic field to reach zero at different times. Quantifying these guide fields could potentially increase understanding of the magnetic field on a small scale. Figure 8 shows an example of this in black, where the swept-back feature is seen in the top hodogram; however, the linear relationship seen in the hodogram is shifted upwards.

Other prominent signatures of aperiodic waves include the "swept forward" signature, an example of which is found in purple in figure 8. As the magnetic field is confined by the solar wind, the dusk sector exhibits magnetic field that is swept forward from the rotation rate of the planet. This magnetic field is pushed forward and is seen in MAG data as an in-phase relationship between radial and azimuthal field components. Figure 8 shows this as a positive linear relationship between $\mathbf{B}_r$ and $\mathbf{B}_\varphi$ in the top hodogram.

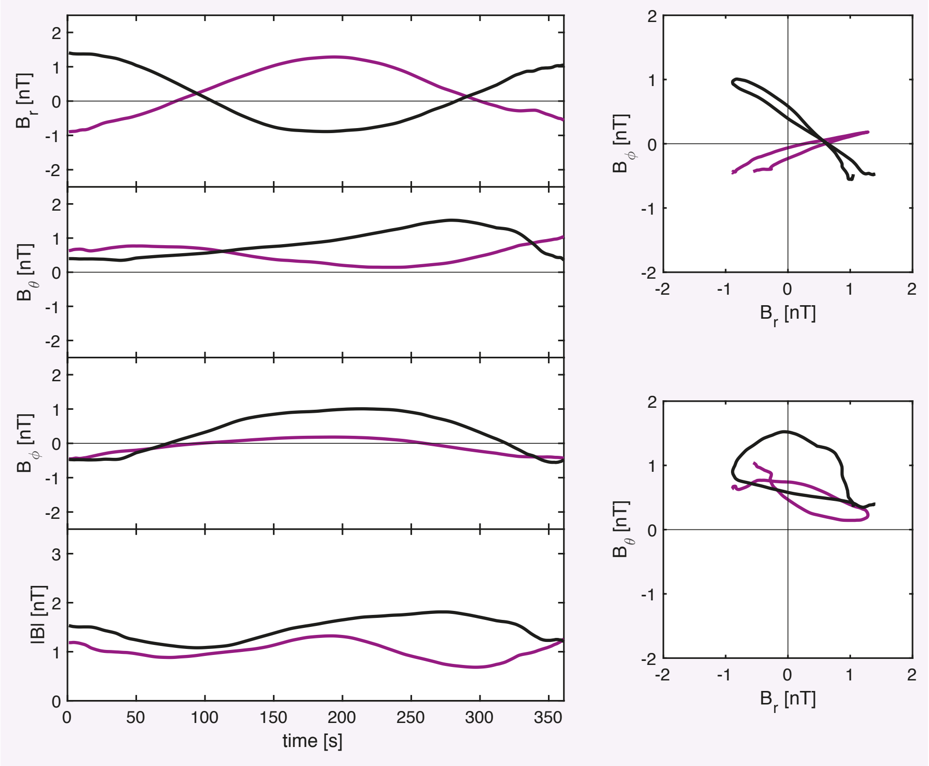
The study of these smaller and unpredictable waves provides a key insight into small-scale happenings near the current sheet. Their origin and effects can lead to understanding of the magnetic and plasma environments of Saturn's largest moon Titan as well as the equatorial region of the magnetosphere. This can all be achieved by modelling the current sheet as it is deformed by a wave.

Future work

The first steps to modelling the aperiodic waves is to have a local model of the current sheet. This is achieved by using a Harris current sheet for the radial and azimuthal field components and a constant field value in the $\hat{z}$-direction (Harris 1962). At the centre of the current sheet the magnetic field magnitude should be at a minimum; it then increases as you travel in the $\hat{z}$-direction away from the current sheet, reaching



7 An example of an aperiodic wave seen in 2009 by the Cassini magnetometer in spherical coordinates where $\hat{r}$ is radial, $\hat{\theta}$ is azimuthal and $\hat{\phi}$ completes a right-handed system ($\hat{\theta}$ is southward at the equator). The bottom panel shows the magnetic field magnitude during the event, displaying the characteristic "w" shape. To the right, two hodograms show the relationship between magnetic field components. In this example the field is swept forward and so we see a negative linear relationship in the top hodogram.



8 Example of two aperiodic waves on the current sheet. The purple line indicates a swept forward field during the event, where the top hodogram to the right shows a positive linear relationship, and the black line shows a "shifted" event where the hodogram is pushed upwards from zero.

a constant value within the lobes of the magnetosphere. When fixing this condition in one field component, as discussed above, the radial component is positive above the sheet and negative below; then the profile of the magnetic field component will follow a hyperbolic tangent function. Additionally, the same hyperbolic tangent function can be used to model the azimuthal field. However, depending on the direction that the field is swept – backwards or forwards with rotation – the hyperbolic tangent function is negative (backwards) or positive (forwards). The third and final magnetic field component in cylindrical coordinates is $\hat{z}$, which is kept at a constant value, lower than the radial and azimuthal components. However, this component can be modulated by the passing wave, and so as the field is deformed by a wave this can lead to different signatures in $\mathbf{B}_z$.

Now, we need to model the deformation of the current sheet as a wave travels along it. To do this we use the method laid out in Tsyganenko (1998). This methodology uses Euler potentials to ensure that the deformed magnetic field satisfies Maxwell's equations. A Gaussian wave pulse is chosen and propagated down the current sheet to simulate a wave. The Harris sheet and the Gaussian pulse all have variables that can be fitted to the data from MAG and can be used to estimate parameters relating to the wave, as well as the current sheet properties, such as thickness and magnetic field values of the lobes. The first lobe denotes the area of the magnetosphere in which the magnetic field is radially outward above the current sheet, and the second lobe is where the field is radially inward below the current sheet, analogous to the lobes in Earth's magnetotail. Amplitudes, angular frequency and wave vector can be fitted to the MAG data, all in aid of understanding the origin and effects of these waves.

Preliminary results show local time and radial differences in current sheet structure and wave parameters, most notable will be the resolution of wave propagation direction using the radial and azimuthal wave vectors. Magnetic field lobe values and scale height analysis can be used to validate the fitting of the variables with the current sheet model with a Gaussian wave deformation. ●

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RISHBETH PRIZE

Carley Martin won a Rishbeth Prize 2016 for the best MIST postgraduate talk at the National Astronomy Meeting in Leicester. The awards remember Henry Rishbeth, a founder of the Magnetosphere, Ionosphere, Solar–Terrestrial community.

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