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How does the Sun Influence the Magnetospheres of Jupiter and Saturn?

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Abstract. Spacecraft have visited Jupiter and Saturn at all phases of the solar cycle and thus we have a wealth of data with which to explore both upstream parameters and magnetospheric response. In this paper we review upstream parameters including interplanetary magnetic field strength and direction, solar wind dynamic pressure, plasma beta and Mach number. We consider the impact of changing solar wind on dayside coupling via reconnection. We also comment on how solar UV flux variability over a solar cycle influences the plasma and neutral tori in the inner magnetospheres of Jupiter and Saturn, and thus estimate the solar cycle effects on internally driven magnetospheric dynamics. Finally we place our results in the context of the now complete set of data from the Cassini mission at Saturn and the current data streaming in from Juno at Jupiter, outlining future avenues for research.

Keywords. Jupiter, Saturn, solar wind, interplanetary medium, UV radiation, planets and satellites: general, molecular processes

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The magnetospheres of Jupiter and Saturn are fascinating environments. Their dynamics are often said to be dominated by internal factors associated with strong planetary magnetic fields, rapid planetary rotation as an energy source, and internal plasma loading from moons and rings (e.g. Vasyliunas 1983; Hill 2017, and references therein). However, there is also evidence that Jupiter and Saturn respond to forcing from their external environment, the solar wind. Thus, characterising the upstream environment is critical to understand this internal vs. external balance. Both planets have been visited by multiple spacecraft. Saturn has hosted the orbiting Cassini spacecraft since 2004, completely changing our understanding of this beautiful planet, and Jupiter has recently seen the arrival of the Juno spacecraft. Figure 1 shows the variation of sunspot number with time from 1970 to 2017, with the times of spacecraft flybys and orbital tours. It illustrates that there has been spacecraft coverage at both Jupiter and Saturn at every phase of the solar cycle, and we have significant heritage datasets from which to draw a statistical picture of the large-scale structure of the solar wind, as well as plenty of in situ magnetospheric measurements to elucidate the magnetospheric response to external driving.

1. Solar wind properties

The interplanetary magnetic field (IMF) evolves with increasing radial distance from the Sun. One manifestation of this is the increasing winding of the field associated with the Parker Spiral (e.g. Forsyth *et al.* 1996). The measured azimuthal angles at Jupiter and Saturn are broadly in line with theory, with some small solar cycle-linked deviations which may be traced to displacements of the heliospheric current sheet (HCS) out of

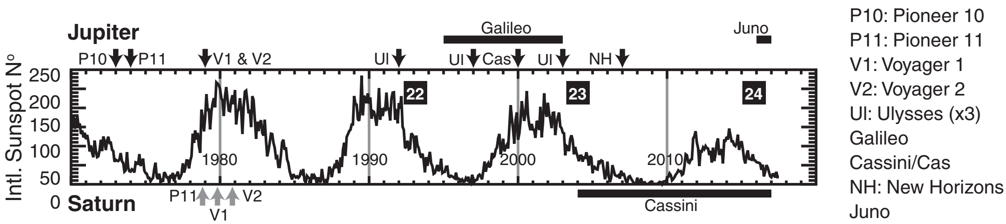

Figure 1. Schematic showing sunspot number with the timings of spacecraft close encounters (arrows) and orbital tours (horizontal bars) at Jupiter (top) and Saturn (bottom). Solar cycle numbers are in squares near each solar maximum. After Jackman & Arridge (2011). Sunspot data source: WDC-SILSO, Royal Observatory of Belgium, Brussels.

the ecliptic (e.g. Jackman *et al.* 2008; Jackman & Arridge 2011). In addition, patterns and sector structure in the IMF can develop significantly between Earth and 5-9 AU. For example, Cassini found the IMF upstream of Saturn during the declining phase of solar cycle 23 to be highly structured by compressions and rarefactions associated with Corotating Interaction Regions (CIRs) (e.g. Jackman *et al.* 2004). This structure is due to the tilt of the Sun's dipole and the interaction between fast and slow streams of solar wind. Hanlon *et al.* (2004) showed that this regular phasing can be disrupted somewhat by the merging of compression regions as the solar wind develops. However, when the phasing of compressions and rarefactions is regular, this property can be used to infer solar wind conditions even when a spacecraft is inside the magnetosphere (e.g. Bunce *et al.* 2005). Characterisation of the IMF upstream of Jupiter, during the declining phase of solar cycle 24, will be important for the interpretation of Juno data (Ebert *et al.* 2014).

Solar wind plasma parameters also change over the solar cycle, and between solar cycles, and also with heliocentric distance. Jackman & Arridge (2011) examined the distributions of dynamic pressure, plasma beta and Mach number from spacecraft upstream of both Jupiter and Saturn (Figure 2, with Saturn plasma data based on Pioneer and Voyager at solar maximum only). The Mach number distributions at both planets show highly supersonic and super-Alfvénic flow. At Jupiter the solar wind was more super-magnetosonic and super-Alfvenic at solar minimum. McComas *et al.* (2013) reported on a long-term trend for reduction in solar wind dynamic pressure, mirrored in the trends for solar wind speed, temperature and thermal pressure. If this trend continues it may have significant implications for solar wind-magnetosphere interactions in the coming years.

2. Solar wind-magnetosphere coupling

Some of the greatest debates in the outer planets community have arisen when considering the solar wind-magnetosphere interaction. One element of this debate is the role of viscous interactions between the magnetosheath flow and the magnetosphere (e.g. Axford & Hines 1961). In particular, at the giant planets this viscous interaction may lead to small-scale reconnection on the flanks and mixed boundary layers (Delamere & Bagenal 2013). Evidence that the viscous interaction can result in momentum transfer from the magnetosphere to the magnetosheath, has been presented for the case of Saturn (Burkholder *et al.* 2017). Furthermore, Delamere & Bagenal (2013) argue that the best analogy for the solar wind-gas giant magnetosphere interaction may be one of an Alfvénic solar wind-comet interaction.

In the magnetic reconnection model, the role of dayside reconnection is a topic of intense debate at the outer planets, with limited observations and numerous theoretical arguments about its relative importance. Estimates of the rate of dayside reconnection

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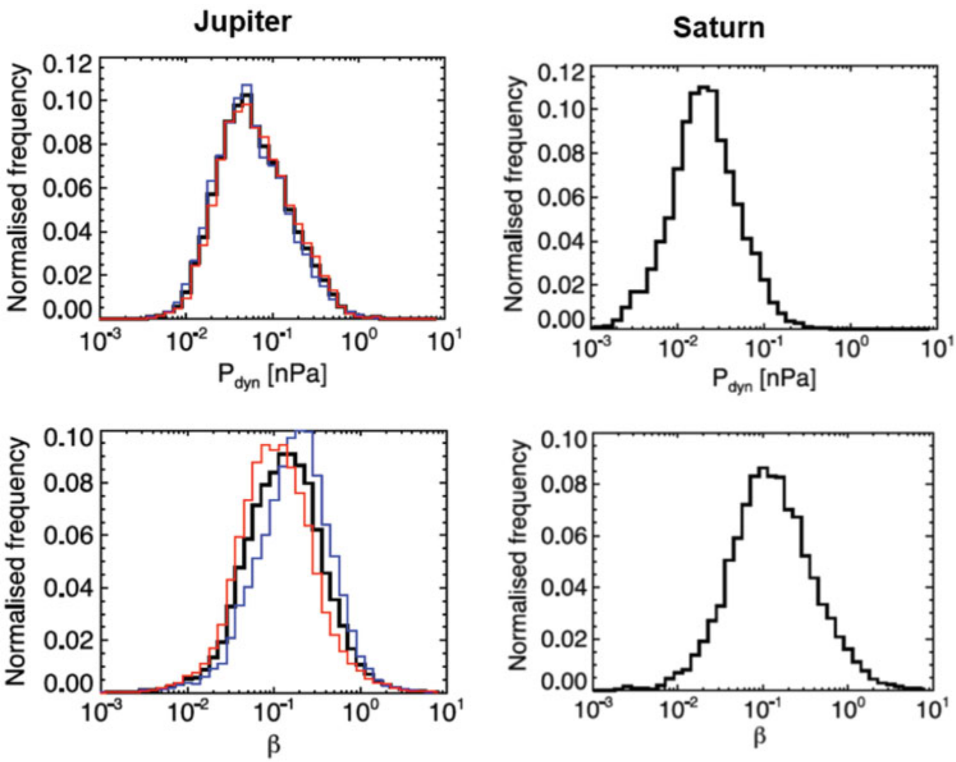

Figure 2. Distributions of solar wind dynamic pressure (top left) and solar wind plasma beta (bottom left) upstream of Jupiter with black indicating all points, blue solar minimum, and red solar maximum. The distributions have been normalised to the total number of points. The right-hand plots represent the same parameters upstream of Saturn for solar maximum only (black). Based on the databases outlined in Jackman & Arridge (2011) and following figures 4 and 5 from that paper.

rate (given as a voltage) have been obtained by adapting empirical relationships from Earth (e.g. Milan *et al.* 2004). One such relationship is shown in Eq. 2.1.

$$\Phi = V_{\rm SW} B_{\perp} L_0 \cos^4(\theta/2) \tag{2.1}$$

where Φ is the reconnection voltage, $V_{\rm SW}$ is the solar wind velocity, $B_{\perp}$ is the strength of the IMF in the T-N plane perpendicular to the velocity vector, θ is the 'clock angle' between the IMF vector and the planet's magnetic axis projected onto a plane perpendicular to the Sun-planet direction, and L_0 is the width of the solar wind channel in the T-N plane (perpendicular to the $B_{\perp}$ vector) in which the IMF reconnects with closed planetary field lines (Jackman *et al.* 2004; Nichols *et al.* 2006). The L_0 value is assumed to be approximately half the subsolar standoff distance (Milan *et al.* 2004). For Saturn, this gives voltages of $\sim$ 100 kV in compression regions, and $\sim$ 10 kV in rarefaction regions, compared to a long-term average voltage of $\sim$ 40 kV (Masters 2015).

Case studies show the evidence of dayside reconnection at Saturn and Jupiter, via in situ observations of accelerated flows and flux transfer events (e.g. McAndrews *et al.* 2008; Jasinski *et al.* 2016b; Ebert *et al.* 2017), and indirect observations of solar wind plasma in the cusp (e.g. Arridge *et al.* 2016; Jasinski *et al.* 2016a). However, the debate centres around the efficiency of dayside reconnection and its global effects. There are three factors which are debated as to their effects on the efficiency; i) There is conflicting

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evidence that efficiency changes with increasing magnetosonic Mach number (e.g. Scurry & Russell 1991; Grocott *et al.* 2009); ii) It is suggested that reconnection efficiency may decrease under conditions of large magnetosheath plasma beta (e.g Sonnerup 1974; Masters *et al.* 2012), but the consensus appears to be that the difference in plasma beta across the magnetopause is more important than the absolute value (Masters *et al.* 2012); iii) There is evidence of more severe diamagnetic drift suppression at Saturn (compared to Earth) which limits reconnection onset to higher magnetic shear conditions (Fuselier *et al.* 2014). This need not switch off reconnection, but may mean the reconnection site moves to higher latitudes, with associated implications for open flux addition.

3. Summary and future directions

The solar wind and IMF upstream of Saturn and Jupiter make for a dynamic environment, and provide valuable information about the radial evolution of the heliosphere. In the absence of upstream monitors there is often heavy reliance on MHD propagations of solar wind observations from 1 AU (e.g. Zieger & Hansen 2008). These models have proved to be useful tools but they have limitations, particularly their inability to propagate IMF B_N, important in predicting dayside reconnection. 3D MHD Heliosphere models, for example ENLIL (Odstrcil 2003), can provide the full IMF and have shown some utility, but they have not been fully validated for outer planet studies.

One of the key differences between Earth and Saturn/Jupiter is that the moons Io at Jupiter and Enceladus at Saturn are particularly important sources of neutrals which form neutral tori and then, through ionisation, dissociation, and charge exchange, form plasma tori. Photoionisation and photodissociation of material from Enceladus is an important reaction, susceptible to modulations in solar EUV over the solar cycle, and over a solar rotation. Fleshman *et al.* (2012) have shown that at solar maximum, neutral abundances due to photodissociation double, although this ultimately has a minor impact due to the importance of charge exchange. Another form of solar driving that is yet to be explored is the effect of changes in ionospheric conductivity (due to EUV or cosmic rays) over the solar cycle. The conductivity affects magnetosphere-ionosphere coupling and so changes can lead to effects on field-aligned currents, accelerating potential drops, and precipitating electron energies. These may have observable consequences for auroral emissions. This may also affect the ionospheres of natural satellites, which may affect the mass-loading of the magnetosphere in a non-linear fashion.

The Cassini dataset provides the unique opportunity to explore a full solar cycle at an outer planet with a single spacecraft. Future work may employ statistical techniques, such as quantile-quantile plotting, to examine how distributions of upstream parameters have changed across the solar cycle (e.g. Tindale & Chapman 2016). The flattened shape of Saturn's magnetopause also plays a role in modulating the magnetosheath conditions at the magnetopause, an aspect only beginning to be addressed, and will no doubt also be examined by Juno at Jupiter (e.g. Pilkington *et al.* 2014; Sulaiman *et al.* 2014).

The magnetospheres at Jupiter and Saturn are very large volumes of space relative to the terrestrial magnetospheres. As such, inferring their time-dependent response to internal and external drivers is a significant challenge. Similar problems are also being addressed for the magnetospheres of Uranus and Neptune (e.g. Arridge 2015). Rising to this challenge will require the integration of upstream parameters, in situ data, remote sensing data (e.g., energetic neutral atoms, auroral and molecular/atomic torus emissions), and models. Data assimilation may also be important in using these hetrogeneous data sets to establish a system-level picture of giant planet space weather.

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