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V. Kaminker

University of Alaska, Fairbanks

P. A. Delamere

University of Alaska, Fairbanks

C. S. Ng

University of Alaska, Fairbanks

T. Dennis

University of Alaska, Fairbanks

A. Otto

University of Alaska, Fairbanks

See next page for additional authors

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Authors

V. Kaminker, P. A. Delamere, C. S. Ng, T. Dennis, A. Otto, and X. Ma

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Key Points:

- Saturn's magnetodisc exhibits local time asymmetry in terms of magnetic fluctuations
- Magnetic fluctuations are quantified in terms of turbulent heating
- The fluctuations are consistent with regions where magnetic reconnection associated with internal flux circulation is operating

Correspondence to:

P. A. Delamere,
padelamere@alaska.edu

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Local time dependence of turbulent magnetic fields in Saturn's magnetodisc

V. Kaminker¹ , P. A. Delamere¹, C. S. Ng¹ , T. Dennis¹ , A. Otto¹ , and X. Ma¹
¹Geophysical Institute, University of Alaska Fairbanks, Fairbanks, Alaska, USA

Abstract Net plasma transport in magnetodiscs around giant planets is outward. Observations of plasma temperature have shown that the expanding plasma is heating nonadiabatically during this process. Turbulence has been suggested as a source of heating. However, the mechanism and distribution of magnetic fluctuations in giant magnetospheres are poorly understood. In this study we attempt to quantify the radial and local time dependence of fluctuating magnetic field signatures that are suggestive of turbulence, quantifying the fluctuations in terms of a plasma heating rate density. In addition, the inferred heating rate density is correlated with magnetic field configurations that include azimuthal bend forward/back and magnitude of the equatorial normal component of magnetic field relative to the dipole. We find a significant local time dependence in magnetic fluctuations that is consistent with flux transport triggered in the subsolar and dusk sectors due to magnetodisc reconnection.

1. Introduction

The flow of mass and energy in Saturn's magnetosphere has been estimated with both physical chemistry models and empirical constraints [Bagenal and Delamere, 2011; Fleshman et al., 2013]. Water geysers emanating from Enceladus' south pole are the source of roughly 200 kg/s of neutral gas into the inner magnetosphere (see reviews by Achilleos et al. [2015] and Delamere et al. [2015a]). Much of this neutral vapor is lost due to impacts with the planet and rings or via fast neutral escape following charge exchange reactions. The net mass lost through radial transport of plasma is roughly 1/4 of the neutral source, or ~60 kg/s. Interestingly, the plasma is heated during radial transport with an empirically determined power input of 75–630 GW [Bagenal and Delamere, 2011].

Case studies of turbulent magnetic field fluctuations within Saturn's magnetodisc have been conducted, and von Papen et al. [2014] suggested that a turbulent cascade can provide 60–100 GW of heating power based on estimates of the plasma heating rate density from strong kinetic Alfvén wave (KAW) turbulence. Due to uncertainty of the location of the magnetopause boundary, von Papen et al. [2014] limited their analysis to a radial distance from 6 R_S to 17 R_S ; therefore, the volume integration yielding 60–100 GW would represent a lower limit. In addition, their analysis did not consider local time variations.

In this paper, we build on our previous analysis of magnetic flux circulation and examine the local time dependence of turbulent magnetic field fluctuations in Saturn's middle and outer magnetosphere using our catalogue of magnetopause boundary crossings from 2004 to 2012 [Delamere et al., 2015b]. Figure 1 shows our boundary identifications for each Cassini orbit from 2004 to mid-2012 (blue = magnetosphere, red = sheath, and green = solar wind) based on Cassini magnetometer data (MAG) and plasma data (CAPS). Our time series analysis and estimate of MHD and KAW turbulence follows the basic methods of Saur [2004] and von Papen et al. [2014], respectively, but our interpretation is guided instead by the necessity of magnetic reconnection to facilitate the mandatory flux circulation within Saturn's magnetodisc. We find a strong correlation between turbulent heating and magnetic reconnection in the subsolar and dusk sectors.

1.1. Magnetic Flux Circulation

Mass is lost to the solar wind at a rate of ~60 kg/s [Fleshman et al., 2013]. As mass is transported radially outward, magnetic flux is expelled from the inner magnetosphere and tends to accumulate in the outer magnetosphere, forming a "cushion" region where the equatorial B_θ component is larger than the dipole [Delamere et al., 2015b]. (We note that our definition of the cushion region differs from previous studies, e.g. Went et al. [2011], where the cushion is defined as a region of quasi-dipolar flux tubes lacking a stretched

Figure 1. Saturn's boundary identification. Blue = magnetosphere, red = sheath, and green = solar wind. The dashed lines are model magnetopause locations for high/inner (0.1 nPa), nominal (0.01 nPa), and low/outer (0.001 nPa) solar wind dynamic pressure [e.g., Kanani et al., 2010; Pilkington et al., 2014]. Image from Delamere et al. [2015b].

magnetodisc configuration.) However, this process cannot proceed indefinitely unless there is a mechanism to return magnetic flux to the inner magnetosphere. For example, magnetic reconnection facilitates the requisite flux circulation.

Two quantities used for assessing radial transport include flux tube mass and flux tube entropy. A negative radial gradient of flux tube mass is unstable to centrifugally-driven flux tube instabilities, while an increasing flux tube entropy profile can stabilize the magnetodisc [Southwood and Kivelson, 1987]. The steady addition of mass in the inner magnetosphere requires an average outward plasma transport. In the magnetodisc and tail this outward transport stretches field lines, which can facilitate reconnection. Reconnection is an essential ingredient in the transport process, generating the requisite low entropy flux tubes in the middle and outer magnetosphere that are necessary to return flux to the inner magnetosphere. For example, tail reconnection involving low density lobe flux in Earth's magnetotail generates low entropy flux tubes that can move rapidly inward as bursty bulk flows [e.g., see reviews by McPherron, 2015 and Otto et al., 2015]. Similarly, lobe reconnection in Saturn's magnetotail likely occurs during solar wind compression events [Jackman, 2015; Thomsen et al., 2015], generating impressive auroral storms and energetic particle emissions [Mitchell et al., 2015]. However, Delamere et al. [2015b] argue that Saturn's magnetodisc reconnection operates primarily on closed field lines that map to the cushion region in the outer magnetosphere, allowing magnetic flux to return to the inner magnetosphere. Injection events in the inner magnetosphere are well documented [e.g., Paranicas et al., 2016] and may have their origins in the middle and outer magnetospheres.

Delamere et al. [2015b] found that much of the internal reconnection (essentially Vasyliunas reconnection [Vasyliunas, 1983]) required for flux circulation occurs on the dayside and dusk sector, contrary to traditional expectation of nightside Vasyliunas cycle reconnection (see sketch in Figure 2). The reconnection potentials associated with internal flux transport exceeded 300 kV, dominating over large-scale Dungey reconnection associated with the solar wind interaction (i.e., 10–70 kV [Masters et al., 2014]). Using Cassini 1 s magnetometer data (MAG), Delamere et al. [2015b] investigated each current sheet crossing encountered with a 10 min sliding window and found frequent large variations in the radial (B_r) and azimuthal (B_ϕ) magnetic field components. Bend forward/back configurations are identified by an in-phase/out-of-phase relation

Figure 2. Illustration of the magnetic field topology and flux circulation at Saturn. Flows are shown with red arrows. Magnetic fields are shown in purple (mapping to outer magnetosphere) and blue (showing bend back and bend forward configurations). Image from *Delamere et al.* [2015b].

between B_r and B_ϕ at the current sheet encounter. In many instances the normal component (nominally B_θ) was negative, consistent with an X line located planetward of the spacecraft. The larger the bend forward/back the larger the perturbation due to the presumed local reconnection flows. Bend forward configurations are consistent with inward flows that increase azimuthal speed due to conservation of angular momentum. *Delamere et al.* [2015b] also noted that the time between consecutive current sheet (CS) crossings was often approximately tens of minutes, suggesting a filamentary or often highly structured CS, indicating transport operating on small and possibly kinetic scales (i.e., reconnection “drizzle”). These frequently observed magnetically perturbed CS encounters motivate an analysis of turbulence in Saturn’s outer magnetosphere.

1.2. Magnetic Reconnection and Turbulence

Magnetic reconnection is a universal process in nearly all magnetized space and astrophysical plasmas. Preexisting current sheets in a collisionless plasma with a characteristic width of ion kinetic scales are susceptible to reconnection, though the specific dissipation mechanisms for the diffusion region requires electron

kinetic scales. Tearing modes and reconnection convert large amounts of magnetic into thermal and kinetic energy, thereby providing a source of energy to drive turbulence. It is also possible that turbulence satisfying the specific tearing mode conditions (e.g., microinstabilities leading to lower-hybrid-drift or ion-acoustic turbulence) can trigger reconnection [Birk and Otto, 1991]. The relation between magnetic reconnection and large-scale turbulence is not well understood, but results from solar wind observations indicate that reconnection is more likely in intervals with intermittent turbulence [Osman et al., 2014]. Although this does not necessarily imply a causal relation, it may indicate that observed magnetic fluctuations also relate to the presence of local current sheets and energy release processes such as magnetic reconnection.

Any perturbation (e.g., by reconnection, braking of bursty bulk flows [Ergun et al., 2015; Stawarz et al., 2015], or plasma injection events) in a plasma generates Alfvén waves. Counter-propagating Alfvén waves are known to interact nonlinearly, generating turbulence [Iroshnikov, 1963; Chandran, 2004]. If we assume that the shear Alfvén wave represents magnetic fluctuations at large scales, then a turbulent cascade toward the dissipation scale (i.e., ion kinetic scale) would logically invoke kinetic Alfvén waves [Hasegawa and Mima, 1978; Schekochihin et al., 2009]. While in a collisionless plasma it is nontrivial to identify the physical dissipation mechanism (i.e., as distinct from the case of viscosity in a hydrodynamic flow), the kinetic Alfvén wave is a reasonable extrapolation of the shear Alfvén wave to dissipation scales, though the nonlinear interaction between other modes can be considered too (e.g., whistler waves [Dwivedi and Sharma, 2013; Galtier et al., 2005]).

2. Turbulent Plasma Heating Model

2.1. Plasma Turbulent Heating Model

In a turbulent cascade, the energy transfer rate from one scale to another is given by [e.g., Howes et al., 2006; Schekochihin et al., 2009]

$$\epsilon \sim \frac{E_{\text{tot}}}{\tau} \quad (1)$$

where τ is the transfer time scale and E_{tot} is the energy density of turbulent fluctuations where

$$E_{\text{tot}} \sim 2 \frac{\delta B_{\perp}^2}{2\mu_0\rho} \quad (2)$$

with ρ being the mass density. The time scale can be found from the dispersion relation of Alfvén wave packets $\omega \sim k_{\parallel} v_A$ and the displacement δr of the magnetic field where v_A is the Alfvén speed. The displacement of the field per interaction can be estimated from the Walén relation (also valid for nonlinear Alfvén waves)

$$\frac{\delta u_{\perp}}{v_A} = \frac{\delta r \delta t}{\delta t \lambda_{\parallel}} = \frac{\delta B_{\perp}}{B_0} \quad (3)$$

where δt is the interaction time, so that

$$\delta r = \frac{\delta B_{\perp}}{B_0} \lambda_{\parallel} \quad (4)$$

The fractional change in the dimensions of the wave packet is

$$\chi \sim \frac{\delta r}{\lambda_{\perp}} \sim \frac{\delta B_{\perp}}{B_0} \frac{\lambda_{\parallel}}{\lambda_{\perp}} \quad (5)$$

which determines whether the turbulence is weak or strong. While we will assume strong turbulence in our data analysis, we first discuss briefly the weak turbulence case for completeness.

2.2. Weak Turbulence Model

When $\chi \ll 1$, the leading and trailing portions of the wave packets are only slightly altered by the distortion of the magnetic field line; thus, for weak turbulence many interactions adding randomly, i.e., χ^{-2} , are required to induce a fractional change of order unity [Ng and Bhattacharjee, 1996]. The turbulent cascade time scale is

$$\tau \sim \chi^{-2} \frac{1}{k_{\parallel} v_A} \sim \sqrt{\mu_0 \rho} \frac{B_0}{\delta B_{\perp}^2} \frac{k_{\parallel}}{k_{\perp}^2} \quad (6)$$

The turbulent heating rate density of plasma can be found from the cascade energy transport

$$q_{\text{MHD}} \sim \epsilon \rho \sim \frac{1}{\sqrt{\mu_0^3 \rho}} \frac{\delta B_{\perp}^4}{B_0} \frac{k_{\perp}^2}{k_{\parallel}} \quad (7)$$

which is used in the turbulent heating model for Jupiter by Saur [2004].

2.3. Strong Turbulence Model

In the strong turbulence limit $\chi \rightarrow 1$ the turbulent cascade time becomes

$$\tau \sim \frac{1}{k_{\perp} \delta u_{\perp}} \sim \frac{\sqrt{\mu_0 \rho}}{k_{\perp} \delta B_{\perp}} \quad (8)$$

The heating rate density for strong turbulence can be calculated as

$$q_{\text{MHD}} \sim \frac{\delta B_{\perp}^3 k_{\perp}}{\sqrt{\mu_0^3 \rho}} \quad (9)$$

The dispersion for kinetic Alfvén waves (KAW) has the form [Hasegawa, 1976]

$$\omega^2 = k_{\parallel}^2 v_A^2 \left[1 + k_{\perp}^2 \rho_i^2 \left(\frac{3}{4} + \frac{T_e}{T_i} \right) \right] \quad (10)$$

where $\rho_i = \frac{\sqrt{m_w K_B T}}{Ze B_0}$ is the ion gyroradius and $T_{e,i}$ is the electron/ion temperature. In the limit $k_{\perp}^2 \rho_i^2 \geq 1$ the dispersion relationship becomes $\omega^2 \rightarrow k_{\parallel}^2 v_A^2 k_{\perp}^2 \rho_i^2$. Using the Walén relationship for strong turbulence, the cascade time scale can then be written as

$$\tau \sim \frac{1}{k_{\perp}^2 \delta u_{\perp} \rho_i} \quad (11)$$

so that for strong turbulence the heating rate density in the kinetic dissipation scale is

$$q_{\text{KAW strong}} \sim \frac{1}{\sqrt{\mu_0^3 \rho}} \delta B_{\perp}^3 k_{\perp}^2 \rho_i \quad (12)$$

3. Data Analysis

3.1. Magnetometer Data Analysis

The Cassini magnetometer (MAG) [Dougherty *et al.*, 2004] was used to observe fluctuations of the magnetic field in Saturn's magnetosphere. Power spectral analysis of the 1 s averaged Cassini magnetometer data was then used to calculate the heating rate density in the magnetodisc (e.g., $\pm 30^\circ$ latitude with respect to the planet equator) as a function of local time and radial distance. Note that we do not account for warping of the magnetodisc but instead take a broad range of latitudes to capture the current sheet [Arridge *et al.*, 2008]. Magnetometer data were analyzed in Saturn-centered spherical KRTP (Kronocentric R Theta Phi, standard right-handed spherical triad for a planet-centered system) coordinates, where $\hat{\mathbf{e}}_r$ is the radial coordinate from Saturn. The azimuthal coordinate $\hat{\mathbf{e}}_{\phi}$ is perpendicular to both $\hat{\mathbf{e}}_r$ and the direction of rotation of the planet $\hat{\mathbf{e}}_{\Omega}$, and is positive in the direction of corotation. The θ component $\hat{\mathbf{e}}_{\theta} = \hat{\mathbf{e}}_{\phi} \times \hat{\mathbf{e}}_r$ completes the right-handed coordinate system. Following Delamere *et al.* [2015b], 10 min windows were selected to conduct the spectral analysis. Larger windows can be contaminated by fluctuations associated with boundaries between flux tubes with different plasma characteristics (e.g., low- versus high-entropy flux tubes). This window size is also optimal for capturing the transition between the inertial subrange (MHD scale) and the dissipation subrange (KAW/kinetic dissipation scale) so that, whenever possible, a comparison of the heating rate density in the inertial and kinetic ranges can be made. In general, we use the kinetic range since this captures the cascade to dissipation scales.

The sample mean magnetic field is determined by the time average of magnetic field over the 10 min sampling window $\mathbf{B}_0 = \langle \mathbf{B}(t) \rangle$. The perturbation of the magnetic field is then $\delta \mathbf{B}(t) = \mathbf{B}(t) - \mathbf{B}_0$, and perpendicular fluctuations of the magnetic field are given by $\delta \mathbf{B}(t)_{\perp} = \delta \mathbf{B}(t) - \delta \mathbf{B}(t)_{\parallel}$, where $\delta \mathbf{B}(t)_{\parallel}$ is the component of the fluctuation of the magnetic field parallel to $\mathbf{B}_0$. The power spectrum of vector components of $\delta \mathbf{B}(t)_{\perp}$ is then estimated as in Tao *et al.* [2015]:

$$P(f) = \frac{2}{N \Delta t} \sum_{i=1}^N \Delta t |W_i(t_i, f)|^2$$

where $W_i(t_i, f)$ is a Morlet wavelet with the period of $(1.03f)^{-1}$ [Farge, 1992; Torrence and Compo, 1998]. The total power spectrum of the perpendicular fluctuation is calculated as the square root of the sum of the squares of the components.

Figure 3. Calculation of heating rate density from the power spectrum using MHD and KAW turbulence models. A strong magnetohydrodynamic turbulence model is used to calculate the heating rate density in the inertial subrange of the power spectrum [3×10^{-3} Hz, $\frac{1}{1.5} \Omega_i$]. A strong kinetic Alfvén Wave turbulence model is used to calculate the heating rate density in the kinetic dissipation subrange of the power spectrum [$1.5 \Omega_i$, 1×10^{-1} Hz].

3.2. Turbulent Heating Calculation

Following the turbulent plasma heating analysis of *von Papen et al.* [2014], the heating rate density is calculated from observed power spectra, $P(f)$, of the magnetic field fluctuations. By definition, $\delta b^2 \sim P(f)f$ [*Leamon et al.*, 1999]. Therefore, the strong turbulent heating rate density can be calculated as

$$q_{\text{KAW}} = \frac{\delta b_s^3 k_{\perp}^2 \rho_i}{\sqrt{\mu_0^3 \rho}} \quad (13)$$

in the kinetic dissipation subrange and as

$$q_{\text{MHD}} = \frac{\delta b_s^3 k_{\perp}}{\sqrt{\mu_0^3 \rho}} \quad (14)$$

in inertial subrange, where $k_{\perp} = \frac{2\pi f}{v_{\text{rel}} \sin(\theta_{vB})}$ [*von Papen et al.*, 2014]. Scale height, plasma density, and temperature for water species were modeled using empirical relations from *Thomsen et al.* [2010] and assumed to be constant over the sample window.

The heating rate density was calculated from power spectra as follows: The strong MHD turbulence model equation (14) was used to calculate the heating rate density of plasma from the power spectrum with

Figure 4. Correlation of q_{MHD} and q_{KAW} . Comparison of heating rate density in MHD and in KAW subregions. This histogram depicts a comparison of the order of magnitude difference between the MHD and KAW calculations.

frequencies between 3×10^{-3} Hz and the gyration frequency of water ions divided by 1.5. The strong KAW turbulence model equation (13) was used to calculate turbulent plasma heating rate density from the power spectrum between 1.5 times the gyration frequency of water ions and 1×10^{-1} Hz. The heating rate density was calculated across frequencies in the analyzed subrange and then averaged (see example case in Figure 3). Cases where the heating rate density fluctuates by 2 or more orders of magnitude across the analyzed frequencies were discarded. Uncertainty stems from empirical estimates of $k_{\perp}$ and ρ as well as the limited range of frequencies used in the analysis. The latter issue can produce order of magnitude variations in the power of the perturbations, but the smaller sample window mitigates against measuring fluctuations due to spatial structures moving past the spacecraft.

In some cases both the inertial subrange and the kinetic dissipation subrange are present in the power spectrum, so that both MHD and KAW turbulent models can be used to calculate the heating rate density in the given sample window. This allows a comparison of the two models in a systematic way (Figure 4). We present the comparison as a histogram of the difference of the order of magnitude between the two values. The plasma heating rate density using a KAW model produces somewhat higher values than the MHD model.

We used a hybrid model of the turbulent plasma heating in Saturn's magnetosphere by selecting the MHD model when the power spectrum is in the inertial subrange and the KAW model when the power spectrum is

Figure 5. Histogram of spectral indices for the kinetic subrange. The vertical line indicates a slope of $-7/3$.

Figure 6. Histogram of spectral indices for the MHD subrange. The vertical line indicates a slope of $-5/3$.

in the kinetic dissipation subrange. When both ranges are represented in the power spectrum, the KAW model was used, assuming that the KAW model best represents the cascade to dissipation scales. Note that the systematically larger KAW heating rate densities will give an upper limit for the power input to the magnetodisc. Figures 5 and 6 show the distribution of spectral indices for the KAW and MHD subranges with the solid line indicating the expected values of $-7/3$ for the KAW subrange [e.g., Galtier et al., 2005] and $-5/3$ for the MHD subrange (i.e., Kolmogorov prediction). Slopes within 2 standard deviations from the mean were used in the analysis.

4. Results

4.1. Asymmetric Turbulent Heating of Plasma in Saturn Magnetosphere

We identified the magnetospheric boundary for the Cassini orbits from 2004 to 2012 using Cassini's Plasma Spectrometer (CAPS) [Young et al., 2004] ions singles data, CAPS electron spectrometer, and the 1 s averaged MAG data [Dougherty et al., 2004] shown in Figure 1. The plasma heating rate density was analyzed at various locations around the planet to build a physical picture of turbulent processes. Figure 7 is a polar map showing the turbulent heating. The geometric mean of the hybrid heating rate density is evaluated over spherical bins of the size of $1 R_S$, 1 h local time (LT), and 30° latitude.

Figure 7. Turbulent heating of plasma around Saturn. This polar map of heating rate density indicates a local time asymmetry of turbulent processes, with an active region on the dayside to dusk sector and a quiet region in the postmidnight sector. The color map is in units of W/m^3 .

Figure 8. Average heating rate density in the region $[20, 30] R_S$ as a function of local time. This demonstrates a significant local time asymmetry, with an active region at $[10, 20]$ LT and a quiet region at $[3, 9]$ LT. The shaded regions indicate where gaps in radial coverage exist.

The magnetopause boundaries are indicated, following *Kanani et al. [2010]* for high/inner (0.1 nPa), nominal (0.01 nPa), and low/outer (0.001 nPa) solar wind dynamic pressures. The region inside of $6 R_S$ was excluded. Note that the heating rate density demonstrates a significant local time asymmetry of turbulent heating, with an active region on the dayside to dusk sector and a quiet region in the postmidnight sector. To further illustrate the asymmetry, Figure 8 shows the heating rate density as a function of local time, averaged using a geometric mean in radial distance from 20 to $30 R_S$. The active region is located from roughly 10 LT to 20 LT, and a quiet region is roughly at 3 LT to 9 LT. This is consistent with the pattern of magnetodisc reconnection identified by *Delamere et al. [2015b]*. While many hundreds of data points contribute to each LT bin, we have shaded regions in grey where radial coverage in the range $[20, 30] R_S$ is incomplete. This comparison including all LT is only valid if we assume radially independent heating rate densities.

4.2. Magnetic Geometry

Due to conservation of angular momentum of corotating plasma, bend back is an expected configuration of the magnetic field in the magnetosphere. However, the bend forward configuration can be achieved due to extraordinary fluctuations of the field due to, for example, a reconnection event. A bend forward configuration, as defined with respect to a local current sheet crossing, occurs when $B_\phi \text{sign}(B_r)/|B_0| > 0$, and bend

Figure 9. A plot showing a two-dimensional histogram of the observed power spectra binned by heating rate density and magnetic field azimuthal bend. The histogram demonstrates a general increase in turbulent heating with increasing forward bend of the field.

Figure 10. A histogram of heating rate density as a function of the azimuthal bend. Correlation of heating rate density and azimuthal bend of the magnetic field in the quiet region of Saturn's magnetodisc [3, 9] LT. Values are tightly grouped at a lower heating rate [10^{-19} , 10^{-18}] W/m³ and a slight negative bend $\approx -\frac{1}{2}$.

back configuration requires that $B_\phi \text{sign}(B_r)/|B_0| < 0$. Note that this definition does not necessarily apply to global field geometry, but rather, it could simply identify a local Alfvénic perturbation. Figure 9 shows a two-dimensional histogram of observed power spectra binned by heating rate density and azimuthal bend of the magnetic field. The histogram demonstrates a general increase in turbulent heating with the increase in the forward bend of the field. On average, the heating rate density of bend forward cases is ~ 2 orders of magnitude higher than for the bend back cases. Figure 10 isolates the quiet region of the magnetosphere located at [3, 9] LT. The heating rate density values are tightly grouped between 10^{-19} and 10^{-18} W/m³, corresponding to lower heating than other parts of Saturn's magnetosphere. Measured values are also tightly grouped around a bend back of the magnetic field with a ratio $B_\phi/|B_0| \approx 1/2$.

The histogram in Figure 11 demonstrates an active region of the magnetosphere located at [10, 20] LT. The heating rate density values are concentrated between 10^{-18} and 10^{-16} W/m³. There is a clear contrast between the active and quiet regions, with heating rates in the active region, on average, 2 orders of magnitude larger than in the quiet region. In addition, the active region has a larger spread of heating rate density values which is indicative, perhaps, of spatially intermittent turbulence and/or a combination of bend forward/back configurations.

Figure 11. A histogram of heating rate density as a function of the azimuthal bend. Correlation of heating rate density and azimuthal bend of the magnetic field in the active region of Saturn's magnetodisc [10, 20] LT. A large number of values are at [10^{-18} , 10^{-16}] W/m³. The spread of values is much larger than in the quiet region.

Figure 12. A histogram of heating rate density as a function of B_θ/B_{dp} . Correlation of the heating rate density and bend of the θ component of the magnetic field in the quiet region of magnetosphere [3, 9] LT. A majority of the values are concentrated around $B_\theta/B_{dp} = 1$. Values in the cushion region $B_\theta/B_{dp} > 1$ are at lower heating rate densities [10^{-19} , 10^{-17}] W/m³. Negative bend is associated with fluctuations of the magnetic field and are associated with higher heating values.

It is also instructive to look at the correlation of the heating rate density and strength of the B_θ component of the magnetic field compared with the strength of the dipole B_{dp} field. The result in Figure 12 implies a correlation of the heating rate density and B_θ/B_{dp} in the [3, 9] LT region. The histogram is plotted on a log scale to highlight infrequent events. A large number of events are grouped around $B_\theta/B_{dp} \approx 1$ as expected. There is a large spread of heating coefficient values in the magnetodisc region $0 < B_\theta/B_{dp} < 1$. In the cushion region where $B_\theta/B_{dp} > 1$, the plasma heating rate density is lower, with the majority of values lying between 10^{-19} and 10^{-17} W/m³. The calm background of the quiet region is occasionally broken by transient events perhaps due to reconnection. Such events are associated with the negative B_θ component. Figure 13 demonstrates the correlation of the heating rate density with B_θ/B_{dp} in the active region. Here it is clear that heating rates in the cushion ($B_\theta/B_{dp} > 1$) are a few orders of magnitude higher than those in the quiet region. Transient events with a negative B_θ component ($B_\theta/B_{dp} < 0$) in the active region appear to be much more frequent and associated with greater heating rate density.

Figure 13. A histogram of heating rate density as a function of B_θ/B_{dp} . Correlation of the heating rate density and bend of the θ component of the magnetic field in the active region of magnetosphere [10, 20] LT. A majority of the values are concentrated around $B_\theta/B_{dp} = 1$. Values in the cushion region $B_\theta/B_{dp} > 1$ are at higher heating rate densities with a higher spread of values than the ones in the quiet region. Negative bend is associated with fluctuations of the magnetic field and are associated with higher heating values.

We can use the heating rate density to estimate the total heating rate of the plasma in the magnetodisc. Using a volume of the magnetodisc from $[8, 20] R_S$ and $[-11, 11]$ degrees latitude, the total heating rate is 62 GW, consistent with *von Papen et al.* [2014] for a similar volume. This value is at the lower range of the power required to heat the plasma reported in *Bagenal and Delamere* [2011]. Alternatively, using $24 R_S$ as a rough separation between the magnetodisc and the cushion, and $B_\theta/B_{\text{tot}} < 1$ as a condition for the magnetodisc region, the total power added is 247 GW. Similarly, using $B_\theta/B_{\text{tot}} > 1$ as a filter for the cushion region, the total heating rate in the radial interval $[24, 30] R_S$ is estimated to be 142 GW. Linear interpolation was used in these estimations to fill areas with missing data. These values give a rough estimate of possible turbulent heating of plasma in the magnetodisc and may represent an upper limit for the reasons discussed in section 1.2. It is also important to note that the magnetic field fluctuations enter the estimate of the heating rate density to the power of 4 or 3 (depending if it is a MHD or KAW case), thus being the strongest driver for order of magnitude estimates of heating rate density. In principle, the correlations with respect to heating rate density should be treated, above all, as correlations with respect to measured magnetic field fluctuations.

5. Summary

Magnetic fluctuations are common in Saturn's magnetodisc. The fluctuations are also known to be locally time dependent with an active region found roughly between 10 and 20 LT. This magnetic activity was suggested by *Delamere et al.* [2015b] to be related to magnetic flux circulation and associated magnetic reconnection within the magnetodisc. In this paper, we have further quantified the fluctuations within the framework of Alfvénic turbulence, estimating the power input into the magnetodisc where we assume a cascade of bulk energy from inertial scales to scales where dissipative processes can convert this energy to heat. We summarize our findings as follows:

1. The magnetic fluctuations in Saturn's magnetodisc can be characterized as quiet between 3 and 9 LT and active between 10 and 20 LT.
2. The active sector corresponds to a region where more frequent magnetic reconnection possibly occurs, based on the bending of the magnetic field and the inferred circulation of magnetic flux [*Delamere et al.*, 2015b].
3. Turbulent heating rates are determined from magnetic fluctuations and large variations in δB lead to orders of magnitude variations in heating rate densities ($q \propto \delta B^3$).
4. In the quiet sector [3, 9] LT, the heating rate density increases with diminishing bend back of the magnetic field, where the limit of a bend forward topology is expected for rapidly inward-moving fluxtubes following reconnection.
5. The large spread of heating rate density values in the active sector [10, 20] LT is consistent with spatially intermittent turbulence and spot heating.
6. Although the statistics are poor, the heating rate densities increase with $B_\theta < 0$ where negative values of B_θ are assumed to be related to reconnection.
7. An upper limit for the magnetodisc heating rate due to turbulence is estimated to be ~ 300 GW, consistent with the estimates of *Bagenal and Delamere* [2011].

While adiabatic acceleration via nonturbulent mechanisms must be considered (e.g., betatron and Fermi acceleration) [*Birn et al.*, 2011], turbulent cascades to dissipation scales and shocks provide promising paradigms for understanding heating in the giant planet magnetodiscs. *Bagenal and Delamere* [2011] calculated 675 GW as an upper limit for the required power input into Saturn's magnetodisc; therefore, we suggest that turbulent heating should not be considered as the only solution to heating. The relative contribution from various heating mechanisms is an open question.

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