Supporting Information for “Saturn’s weather-driven aurorae modulate oscillations in the magnetic field and radio emissions”
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Introduction The following sections provide the reader with further details on the observational design used to collect the data used in this study (Text S1), the reduction steps employed to treat the raw data (Text S2), and the derivation of the key data products presented in the main paper (Text S3). Also included are one supplementary figure (Figure S1) and two supporting tables (Tables S1 and S2).

Text S1 - Observations

The spectral data used for this study were collected over the course of several weeks during June, July and August of 2017. The Near Infrared Echelle Spectrograph (NIRSPEC) (McLean et al., 1998), based at the Keck Observatory atop Mauna Kea in Hawaii, was used to take exposures of Saturn’s northern ionosphere. The instrument slit was trained on the auroral region and stepped down so as to produce a spectral scan of the infrared H$_3^+$ emission in the planet’s upper atmosphere. These observations were previously calibrated and analysed while fixed in local-time in order to show changes on a night-by-night basis (T. S. Stallard et al., 2019). Our processing here follows the same analysis techniques, but instead explores the flows observed at different planetary rotational phases.

This ground-based observing campaign made use of previous designs at Jupiter for scanning the auroral region using the instrument slit (Johnson et al., 2017). Unlike Jupiter, the auroral emission from Saturn is so weak that this technique cannot produce a reasonable signal with most telescopes, and so Keck was used to scan the northern auroral region of Saturn (T. S. Stallard et al., 2019). This dataset represented the first spatially resolved two-dimensional view of the infrared aurora taken from Earth. There were a handful of nights where the instrument was not scanned but instead gathered...
exposures from a single position, akin to previous studies at Saturn (O’Donoghue et al., 2016; Chowdhury et al., 2019, for example). In these instances, the data was processed in the same way thus allowing us to correct for drift within the positioning on the planet, and provided a greatly enhanced signal in the central region of the aurora as a result.

The observing campaign plan was to collect data at the same time as the NASA Cassini mission’s Grand Finale orbits. These highly inclined orbits took the spacecraft on very close passes of the planet’s surface in order to sweep through the magnetic field lines that map through to the auroral regions. The Cassini mission ended on 15 September 2017 with the spacecraft crashing into the upper atmosphere in Saturn’s equatorial region.

While the actual observing sessions did not match up with the timings of the closest approaches of the spacecraft due to observational constraints at Earth, the ground-based observing campaign carried out using Keck was designed to match up as closely as possible with the Grand Finale orbits of the Cassini spacecraft (T. S. Stallard et al., 2019). Realistically, ground-based observations were sometimes typically taken in the days around the closest approach, as was the case with this set of observations.

Table S1 details the observation dates and related night-to-night parameters.

**Text S2 - Data Reduction**

After acquiring all the spectral observations, the raw data were then reduced using previously established techniques (T. S. Stallard et al., 2019). Spectra were first straightened using Keck’s RedSpec data reduction interface, then dark subtracted and flat-fielded to remove any instrumental effects before being flux calibrated using the exposures from standard A0 stars. Since our data was taken with two different Keck-NIRSPEC instru-
ment slit widths across the nights of observation, for the spectra which had a higher spectral resolution (acquired using the 0.288” wide slit as opposed to the 0.432” wide slit), we had to ensure our data matched in spectral resolution when it was co-added. We convolved the higher-resolution data so that its spectral resolution matched that of the lower-resolution data, such that all spectral data could be properly combined.

Our data was combined using the same earlier techniques employed by T. S. Stallard et al. (2019) by assigning individual slit spectra to a two-dimensional map of the planet, using reflected sunlight to find the exact slit position on the planet for each individual spectrum. By subtracting an exposure of reflected sunlight from the rings away from a region of reflected sunlight from both rings and the planet leaves just the reflected sunlight from the surface of the planet. The profile of reflected sunlight from the planet’s surface is then compared with a model of reflected sunlight, calculated as a decrease in brightness from equator to pole as a cosine of double the modulus of latitude (T. S. Stallard et al., 2019).

Once the position from which the slit data was gathered could be determined, the spectral data for each wavelength position along the wavelength axis could be inputted to produce a three-dimensional spectrally mapped data ‘cube’ for each bin. Each cube had two spatial directions (north-south and east-west) and the wavelength direction. The spectral emission was appended to the total north-south range of all positions covered by a slit to ensure that data from the many numerous spectra in a planetary rotational phase bin overlapped accurately. This then allowed us to calculate the Doppler-shift velocity from the H$_3^+$ emission lines for every position within the auroral region. However,
in an earlier study (T. S. Stallard et al., 2019), the data was scanned and stacked for each individual night of observation, blurring out the effects of the rotating planet and highlighting auroral features fixed in local-time, resulting in seven maps of the auroral emission brightness and ion winds for each of the nights of observation.

Here, instead, the data were binned into planetary period phase groupings. Using magnetic data gathered by the Cassini spacecraft (Provan et al., 2018), the northern magnetic phase ($\Psi_N$) for each spectral frame was calculated using the Coordinated Universal Time (UTC) at which the exposure was taken, corrected for the one-way light time from Saturn to Earth. Once the magnetic phase was determined, the spectral exposures were grouped into four different quadrants depending on their central meridian northern magnetic rotational phase, resulting in four binned cubes of spectral images: $\Psi_{0^\circ}$ (with $\Psi_N$ between $315^\circ – 45^\circ$, centered on $0^\circ$), $\Psi_{90^\circ}$ (with $\Psi_N$ between $45^\circ – 135^\circ$, centered on $90^\circ$), $\Psi_{180^\circ}$ (with $\Psi_N$ between $135^\circ – 225^\circ$, centered on $180^\circ$) and $\Psi_{270^\circ}$ (with $\Psi_N$ between $225^\circ – 315^\circ$, centered on $270^\circ$). These groupings were chosen so as to reflect four quarters of a full cycle of possible phases, and to provide both as strong a signal-to-noise ratio as possible and as wide a time coverage as possible in each individual bin.

Table S2 shows the northern phase ranges for each of the four bins and the number of spectra that fall within them, and the total number of spectra that were placed into each of the quadrants of northern magnetic phase. The planetary period oscillation phases obtained from NASA Cassini magnetic field data that have been employed in this study are available from the University of Leicester Research Archive [http://hdl.handle.net/2381/42436] and further detail can be found in Provan et al. (2018).

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Text S3 - Calculating auroral brightness and ion velocities

Following the creation of spectral cubes for each bin, the key emission lines for the tri-hydrogen cation (H$_3^+$) were identified in each cube and fitted using a Gaussian profile of six orders in order to return the spectral intensity, position, width of the line and background fit parameters. These output fit parameters could then be used to derive the emission intensity and ion line-of-sight velocities (Johnson et al., 2017). Figure S1 shows the measured intensities and ion wind velocities and their respective averages at the four binned phase groupings.

Saturn’s ionospheric velocities are dominated by planetary rotation and plasma sub-corotation within the surrounding magnetosphere, so ion flows are fixed in local-time. In this study, we subtract these local-time dependent ion velocities in order to isolate the variation in velocity associated with the phase of the anomalous rotational modulation.

If the ions are driven by the magnetosphere as predicted by various models (G. J. Hunt et al., 2014; G. Hunt et al., 2015), they will always flow over the pole in an anti-sunward direction (as observed from Earth) from $\Psi_N = 0^\circ$ to $\Psi_N = 180^\circ$. As a result, when we observe from Earth, our line-of-sight Doppler shift measurements of these ions would exhibit a red-shift over the pole when the Earth-observed central meridian northern magnetic phase is $\Psi_0^\circ$. Then, half a planetary rotation later, the ions would exhibit a blue-shift over the pole at $\Psi_{180^\circ}$. In other words, these flows are equal and opposite and not fixed in local-time, as they are instead trapped in the frame of Saturn’s magnetic phase.

In Figure 1 of the main paper, we show the ion flows that are expected to be observed when the central meridian northern magnetic phase from Earth is $\Psi_0^\circ$, and highlight the
expected red- and blue-shifts that would be observed across the auroral region for each of the models (G. J. Hunt et al., 2014; G. Hunt et al., 2015) of how the rotational modulation is generated.

In order to isolate the magnetic phase-related velocities, we have to remove the flows associated with local-time velocity flow. We can do this because the velocities measured at $\Psi_0^\circ$ and at $\Psi_{180}^\circ$ consist of two components: the ion flows associated with local-time changes, which we assume are fixed with local-time; and, the ion flows associated with the rotating modulation, which we assume is fixed with rotational phase. As a result, the observed ion flows, $V_{\text{obs}}$, at $\Psi_0^\circ$ and at $\Psi_{180}^\circ$ are the exact opposite of one another. So, at $\Psi_0^\circ$:

$$V_{\text{obs}(0^\circ)} = V_{LT} + V_{0^\circ}$$

and, at $\Psi_{180}^\circ$:

$$V_{\text{obs}(180^\circ)} = V_{LT} + V_{180^\circ}$$

such that:

$$V_{0^\circ} = -V_{180^\circ}$$

where $V_{LT}$ are the ion flows associated with local-time changes. Historic observations of ion line-of-sight velocities at Saturn (T. Stallard, Miller, et al., 2007; T. Stallard, Smith, et al., 2007; Chowdhury et al., 2019; T. S. Stallard et al., 2019, etc.) have shown that measurements of this parameter are generally matched across different studies. This allows us to assume that $V_{LT}$ is largely constant and that, by extension, the magnetospheric flows are in steady-state between measurements acquired at different rotational phases. Since
$V_{0^\circ}$ and $V_{180^\circ}$ are the same flow rotated by 180°, they result in an identical but oppositely directed flow when observed from Earth.

Therefore, we can produce a measured map of emission brightness and ion flows that removes the effect of the rotational modulation ($\Psi_{0^\circ+180^\circ}$), by taking the average velocity from $V_{\text{obs}(0^\circ)}$ and $V_{\text{obs}(180^\circ)}$, as this combines and nullifies the 180° phase difference in rotational modulation velocity:

$$\Psi_{0^\circ+180^\circ} = \frac{[V_{\text{obs}(0^\circ)} + V_{\text{obs}(180^\circ)}]}{2}$$

$$= \frac{[(V_{LT} + V_{0^\circ}) + (V_{LT} + V_{180^\circ})]}{2}$$

$$= \frac{[(V_{LT} + V_{0^\circ}) + (V_{LT} - V_{0^\circ})]}{2}$$

$$= \frac{[2V_{LT}]}{2}.$$

Inversely, we can instead remove the effect of local-time and extract the rotationally modulated ion winds observed at a central meridian phase of $\Psi_{0^\circ}$ by subtracting the observed velocities $V_{\text{obs}(180^\circ)}$ from $V_{\text{obs}(0^\circ)}$:

$$\Psi_{0^\circ-180^\circ} = \frac{[V_{\text{obs}(0^\circ)} - V_{\text{obs}(180^\circ)}]}{2}$$

$$= \frac{[(V_{LT} + V_{0^\circ}) - (V_{LT} + V_{180^\circ})]}{2}$$

$$= \frac{[(V_{LT} + V_{0^\circ}) - (V_{LT} - V_{0^\circ})]}{2}$$

$$= \frac{[2V_{0^\circ}]}{2}.$$

This results in a map of ion winds associated with the rotational modulation alone, shown in Figure 2 in the main paper, as observed in the line-of-sight from Earth with a central meridian of $\Psi_{0^\circ}$ – excluding the local-time component. The same approach can be used to calculate the observed ion winds associated with the rotational modulation.
at a central meridian of \( \Psi_{0^\circ} \). At its core, this approach is identical to the measurement of magnetic field aligned auroral currents made in an earlier study at midnight above the planet by G. J. Hunt et al. (2014). Unlike magnetospheric currents, the ions flow differently depending upon the driver of the current system, and we are able to map these currents across the planet in two dimensions.

Finally, in measuring the line-of-sight flows associated with a central meridian of \( \Psi_{0^\circ} \) we observe all the flows with a vector within the \( \Psi_{0^\circ} - 180^\circ \) direction and have entirely excluded flows in the \( \Psi_{90^\circ} - 270^\circ \) direction. Perpendicular to these are flows moving between phases of \( \Psi_N = 90^\circ \) and \( \Psi_N = 270^\circ \). These are similarly isolated by observing the difference in flows between \( \Psi_{90^\circ} \) and \( \Psi_{270^\circ} \). When we observe the auroral region at a central meridian northern magnetic phase of \( \Psi_{0^\circ} \), ions flow parallel to the plane of our line-of-sight and thus do not exhibit a Doppler-shift. However, having measured these at other central meridian phases, we know that blue-shifted flows at \( \Psi_{90^\circ} \) flow unseen from dusk to dawn at \( \Psi_{0^\circ} \).

As a result, in combining the \( \Psi_{0^\circ} - 180^\circ \) and \( \Psi_{90^\circ} - 270^\circ \) maps, we can reconstruct the flow vectors both towards and away from us (flowing from noon-to-midnight) and perpendicular to \( \Psi_{0^\circ} \) (flowing from dawn-to-dusk) – this combined map is shown in Figure 3 in the main paper.

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Table S1. Details of the observing campaign carried out to collect data for this study. All observation sessions took place over the course of June, July and August 2017. Where the aurora were scanned, the scans could be used to produce a two-dimensional map of the northern polar region. The single-slit position data were then added into the fixed position on the scanned maps. Four rotational bins that match with the phase ($\Psi$) of the magnetic field oscillation resulting from the rotating current system were used to further group the spectral data: $\Psi_0$ (315° to 45°), $\Psi_{90}$ (45° to 135°), $\Psi_{180}$ (135° to 225°) and $\Psi_{270}$ (225° to 315°).

| Date (2017) | Number of spectra | Observation mode | Northern magnetic phase range (°) | Mean northern magnetic phase (°) | Bins covered |
|-------------|-------------------|------------------|-----------------------------------|---------------------------------|--------------|
| 2<sup>nd</sup> June | 108 | Single-slit | 220° to 357° | 289° | $\Psi_0$, $\Psi_{180}$, $\Psi_{270}$ |
| 24<sup>th</sup> July | 80 | Single-slit | 31° to 113° | 72° | $\Psi_0$, $\Psi_{90}$ |
| 25<sup>th</sup> July | 87 | Scan | 104° to 193° | 82° | $\Psi_{90}$, $\Psi_{180}$ |
| 1<sup>st</sup> August | 108 | Scan | 271° to 21° | 326° | $\Psi_0$, $\Psi_{270}$ |
| 7<sup>th</sup> August | 60 | Scan | 54° to 110° | 82° | $\Psi_{90}$ |
| 12<sup>th</sup> August | 78 | Scan | 60° to 140° | 100° | $\Psi_{90}$, $\Psi_{180}$ |
| 14<sup>th</sup> August | 69 | Scan | 225° to 304° | 264° | $\Psi_{180}$, $\Psi_{270}$ |
| 20<sup>th</sup> August | 49 | Scan | 10° to 62° | 36° | $\Psi_0$, $\Psi_{90}$ |
| 25<sup>th</sup> August | 65 | Scan | 20° to 89° | 54° | $\Psi_0$, $\Psi_{90}$ |
Figure S1. $H_3^+$ line emission intensity and line-of-sight velocity maps for each of the four planetary phase bins with corresponding average profiles for these parameters. A co-latitude axis has been employed in order to show distance from the northern Saturnian pole where co-latitude is determined by subtracting the latitude from 90°. The emission intensity maps for $\Psi^0$ (315° to 45°), $\Psi^180$ (135° to 225°), $\Psi^90$ (45° to 135°) and $\Psi^270$ (225° to 315°) are shown in panels (a), (d), (g) and (j), respectively. The corresponding ion line-of-sight velocity maps for $\Psi^0$, $\Psi^180$, $\Psi^90$ and $\Psi^270$ are shown in panels (b), (e), (h) and (k), respectively. Lastly, the average emission intensities and ion winds for $\Psi^0$, $\Psi^180$, $\Psi^90$ and $\Psi^270$ (taken from between the dotted horizontal lines in the maps) are illustrated in panels (c), (f), (i) and (l), respectively.
Table S2. Night-by-night breakdown of Saturn spectra into each of the groupings of northern planetary phase, $\Psi_N$. Four rotational bins that match with the phase of the magnetic field oscillation resulting from the rotating current system were used to bin the spectral data: $\Psi_{0^{\circ}}$ (315° to 45°), $\Psi_{90^{\circ}}$ (45° to 135°), $\Psi_{180^{\circ}}$ (135° to 225°) and $\Psi_{270^{\circ}}$ (225° to 315°). A total of 704 spectral exposures of Saturn’s northern auroral region were grouped into these four quadrants. All spectra were taken using Keck-NIRSPEC over the course of several nights in June, July and August 2017 while the NASA Cassini spacecraft performed its final series of ring-grazing orbits during the Grand Finale phase of the mission.

| Date (2017) | $\Psi_{0^{\circ}}$ (315° to 45°) | $\Psi_{90^{\circ}}$ (45° to 135°) | $\Psi_{180^{\circ}}$ (135° to 225°) | $\Psi_{270^{\circ}}$ (225° to 315°) |
|-------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| 2\textsuperscript{nd} June | 32 | 0 | 18 | 58 |
| 24\textsuperscript{th} July | 13 | 67 | 0 | 0 |
| 25\textsuperscript{th} July | 0 | 33 | 54 | 0 |
| 1\textsuperscript{st} August | 65 | 0 | 0 | 43 |
| 7\textsuperscript{th} August | 0 | 60 | 0 | 0 |
| 12\textsuperscript{th} August | 0 | 72 | 6 | 0 |
| 14\textsuperscript{th} August | 0 | 0 | 1 | 68 |
| 20\textsuperscript{th} August | 34 | 15 | 0 | 0 |
| 25\textsuperscript{th} August | 23 | 42 | 0 | 0 |
| Total spectra | 167 | 289 | 79 | 169 |
| Total nights | 5 | 6 | 4 | 3 |