A brightening of Jupiter's auroral 7.8-μm stratospheric CH_4 emission during a solar wind compression

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Enhancements of mid-infrared emission from CH_4 and other stratospheric hydrocarbons

have been observed coincident with Jupiter's ultraviolet auroral emission[1–6], which demonstrates thermospheric auroral processes and the neutral stratosphere of Jupiter are coupled. However, the exact nature of this coupling has remained an open question. Here, we report evidence that both the morphology and magnitude of Jupiter's auroral CH_4 emission vary on daily timescales in relation to external solar wind conditions. We present a time series of images of Jupiter's auroral 7.8-μm CH_4 emission, as obtained by the COMICS[7] instrument on the Subaru Telescope, between January 11-14th, February 4th-5th and May 17-20th (UT) 2017, allowing the variability of the emission to be assessed over daily to monthly timescales. An increase in the solar wind dynamical pressure at Jupiter from <0.1 nPa to ~ 0.8 nPa was predicted at approximately 22:00 UT on January 11th. From January 11th 15:50 UT (before the solar wind compression) to January 12th 12:57 UT (during compression), the southern auroral CH_4 emission increased in brightness temperature by $\Delta T_b = 3.8 \pm 0.9$ K. On January 12th 16:13 UT (during the compression), the northern auroral emission also exhibited a dusk-side brightening, which mimicks a similar morphology observed in the ultraviolet auroral emission during periods of enhanced solar-wind pressures[8,9]. These results suggest that changes in external solar wind conditions perturb the jovian magnetosphere such that energetic particles are accelerated into the planet's atmosphere, deposit their energy as deep as the neutral stratosphere and modify the thermal structure, abundance of CH_4 or the population of energy states of CH_4. Between mid-January and early-February/mid-May images, the northern auroral CH_4 emission weakened by $\Delta T_b = 4.8 \pm 1.1$ K in the absence of a similar weakening of the southern auroral CH_4 emission. This demonstrates that the north-

ern and southern auroral regions evolve independently as has been determined over longer timescales[10] and in the auroral emission at X-ray wavelengths[11].

7.8-μm Subaru-COMICS (Cooled Mid-Infrared Camera and Spectrograph[7,12]) images were obtained from January 11-14th, February 4-5th and May 17-20th 2017 (UT). Figure 1 shows these measurements following reduction, mosaicking and radiometric calibration (see Methods for further details). A subset of these images is presented in Figures 2 and 3, which show northern and southern polar projections at times when the northern auroral region (henceforth 'NAR', centred at 180°W in system III longitude) and southern auroral region (henceforth 'SAR', between 330-60°W in System III) were visible on the disk of Jupiter. These images demonstrate variability of both the magnitude and morphology of the 7.8-μm CH_4 emission over timescales of days to weeks.

In terms of the morphology, the strongest 7.8-μm emission in both auroral regions appears enclosed inside the statistical mean of the ultraviolet emissions of the main oval[13]. Figure 4 shows the results of ionosphere-to-magnetosphere mapping model calculations[14,15] (see Methods) and demonstrates that the positions of strongest CH_4 emission in the auroral regions predominantly correspond to radial distances of $>$95 R_J: in the outer magnetosphere[16]. The exception is the morphology of the emission in the NAR at 16:13 UT on January 12th (Figure 2a), when a poleward, duskside 'streak' of stronger emission parallel to the eastern boundary of the statistical oval was observed. We have ruled out variable atmospheric seeing conditions between these two nights as the source of this intermittent morphology (see Supplementary Figure 1). As shown in Figure 5, the morphology was observed during a solar-wind compression event that occurred at approximately

22:00 UT on January 11th. A similar morphology of the ultraviolet auroral emission, described as the 'duskside active region', has also been observed during periods of enhanced solar-wind pressures and has been attributed to duskside/nightside reconnection associated with the Vasyliunas or Dungey cycles or velocity shears caused by changing flows on the nightside magnetospheric flank[8,9,17]. Indeed, ionosphere-magnetosphere mapping calculations map 73°N, 155°W (an example location covered by the duskside streak) to $\sim$100R_J at a local time of 19.0 hr. Unlike the NAR, the SAR does not appear to exhibit any smaller-scale morphology although its position at a comparably higher latitude than the NAR does reduce the effective spatial resolution and the ability to resolve smaller scale features. In past studies, the longitudinal position of the southern auroral mid-infrared emission has been considered to move between observations[2,10,18]. While there appear to be subtle changes in the longitudinal position of the southern auroral CH_4 emission in the measurements presented in Figure 3, we attribute this as an artefact of the sub-observer longitude. However, we cannot rule out the longitudinal movement of the southern auroral mid-infrared emission that was observed in past datasets/epochs.

In order to quantify temporal changes in the magnitude of the emission and how they relate to solar-wind conditions, we calculated the residual radiance between Regions 'A' and 'L' for both northern and southern auroral regions. These regions are also shown in Figure 4 and further details of the residual radiance calculation are provided in the Methods section. We will henceforth describe the residual radiance between Region A and Region L as the auroral-quiescent residual. Figure 5 compares the auroral-quiescent residual and uncertainty for both auroral regions and the results of a solar-wind propagation model[19] (see Methods). The solar-wind propagation model predicts the arrival of a solar wind compression at Jupiter at approximately 22:00 UT on Jan 11th, when the solar-wind dynamical pressure was predicted to have increased from less than 0.1 nPa to 0.8 nPa. The auroral-quiescent residual increased from 8.0 ± 0.3 K on January 11th 15:50 UT to 11.8 ± 0.5 K on January 12th 12:57 UT: a net increase of 3.8 ± 0.6 K in brightness temperature or a ∼25% increase in radiance . We note that the viewing geometry of region A in the SAR differed slightly between measurements on these dates ($\mu = cos(\theta_{emm}) = 0.195$ on January 11th 15:50 UT, 0.205 on January 12th 12:57 UT, where θ_{emm} is the emission angle with respect to the local normal). However, forward model calculations (see Methods) demonstrate that differences in the viewing geometry can only explain 0.7 K of the observed brightness temperature change. From January 12th 12:57 UT to January 14th 12:33 UT, the SAR returned to a similar brightness as was observed pre-compression. The SAR auroral-quiescent residual was also similar in magnitude (8.2 ± 0.4 K) several weeks later on February 4th as well as on May 17th and 20th. However, we cannot rule out variability at times intermediate of our measurements.

The NAR was not visible on the disk of Jupiter in the images measured on January 11th (before the solar-wind compression) and so we do not have a reference measurement to determine whether its CH_4 emission also brightened during the solar-wind compression that occurred late on January 11th. However, the aforementioned duskside active emission captured by COMICS on January 12th 16:13 UT occurred shortly after the solar-wind compression, which reiterates that this morphology is likely to be related to enhanced solar-wind conditions and their perturbing effect on the nightside magnetosphere. From January 12th 16:13 UT to January 13th 12:30 UT, the auroral-quiescent residual of the NAR was constant in time within uncertainty (5.7 ± 0.5 K and 5.4 ± 0.3 K respectively). However, between January 13th and February 5th 15:54 UT, the NAR residual decreased significantly to 1.2 ± 1.1 K, which demonstrates that the northern auroral CH_4 emission brightness temperature was comparable to that of a non-auroral longitude and lower latitude. Similarly, measurements in May show the NAR emission to be weak and comparable with, if not weaker, than non-auroral regions. From May 18th to May 19th, there was a marginal increase in the emission in the NAR during a small ($\Delta p_{dyn} \sim 0.2$ nPa) solar-wind compression however, the change was not significant with respect to measurement uncertainty. Without measurements between the dates of January 13th, February 5th and May 18th, it is uncertain whether the NAR emission was consistently weaker in time or whether it exhibited short-term variability and the measurements by chance captured periods of weaker emission. However, we favour the latter possibility given that the February-5th and May-17th measurements were preceded by ≥ 7 days of steady, low pressure ($p_{dyn} < 0.05$ nPa) solar-wind conditions. We also note the findings of a recent analysis of HISAKI-EXCEED[20] observations, which showed the total auroral power during a solar wind compression exhibited a positive correlation with the duration of steady, quiescent solar wind conditions preceding the compression[21]. We also note that the northern auroral C_2H_6 emission weakened during periods of low solar activity in previous work, which similarly suggests a connection with solar conditions on longer timescales[22].

The COMICS 7.8-μm bandpass is predominantly sensitive to Jupiter's CH_4 emission originating in the 20- to 0.5-mbar range (or approximately 100 - 200 km above the 1 bar level), however, there is some sensitivity to pressures as low as the 1-μbar level (see Supplementary Figure 3). A single, broadband measurement of the CH_4 emission does not provide sufficient information to invert or *retrieve* atmospheric parameters and determine at which altitudes they vary. However, the short, daily to weekly timescales over which the CH_4 emission evolves is suggestive of variability in the upper stratosphere-thermosphere (10 - 1 μbar), which has a lower thermal inertia and can respond more rapidly to external forcing in time than the lower stratosphere. For example, the thermal relaxation timescale at 1 μbar is approximately 4 weeks compared to the ∼30 week timescale at the 1-mbar level[23] (although these values are based on the assumption of local thermodynamic equilibrium (LTE)). We suggest the observed changes in CH_4 emission result from either: 1) variable auroral-related heating of the 10- to 1-μbar level, 2) auroral-driven changes in the vertical profile of CH_4 near its homopause at ∼1 μbar, 3) variable non-LTE effects that modify the population of energy states of CH_4 or 4) some combination of 1-3. We performed a series of forward-model calculations, as detailed below, to explore what magnitude and type of changes in the vertical profiles of temperature or CH_4 could give rise to the 3-4 K brightening observed of the SAR following a solar-wind compression.

Forward model calculations were performed using NEMESIS[24]: a forward model and retrieval tool (see Methods). At present, the NEMESIS forward model assumes LTE. Initially, we kept the vertical profile of CH_4 fixed to the 'model A' vertical profile from Moses et al., 2005[25] and modified the vertical temperature profile in the 0.1-mbar to 1-μbar range, which includes the transition from the upper stratosphere to the thermosphere (e.g. see Supplemental Figure 3a). In steady state, thermospheric general circulation models show that the stratosphere-thermosphere transition pressure is deeper in the auroral regions compared to non-auroral regions[26,27]. Yates et al., 2014[28] performed time-dependent thermospheric circulation modelling to investigate the response of the thermospheric structure and circulation to solar wind compressions and expansion events. Between steady (p_{dyn} = 0.021 nPa) and compressed (p_{dyn} = 0.213 nPa) solar wind conditions, the model predicted a $\sim$20 K warming and increase in lapse rate at $\sim$70°N due to increased rates of joule heating at pressures lower than 1 μbar (with the lower model boundary set at 2 μbar). We therefore performed forward model simulations using temperature profiles, where either the thermosphere base pressure or the thermospheric lapse rate was modified. Assuming the thermospheric lapse rate was fixed, the base of the thermosphere would need to be moved approximately a decade of pressure deeper to yield an observed brightness temperature increase of greater than 3 K (see Supplementary Figure 4a). This corresponds to a total temperature increase of more than 100 K at the 0.5-μbar level, assuming a thermospheric lapse rate similar to that measured during Galileo's descent[29]. This is considerably (and unrealistically) larger than the temperature change predicted in the Yates et al. model, even if the solar wind dynamical pressure in their model during the compression was smaller than the magnitude of the pressure predicted on January 11th. Conversely, if the base of the thermosphere was fixed at $\sim$0.2 μbar, the lapse rate in thermosphere would need to be increased by over a factor of 2, from $\sim$2.3 K/km at 0.2 μbar (measured by Galileo[29]) to $\sim$4.7 K/km, in order to yield the observed 3-4 K brightness temperature change (see Supplementary Figure 4b). This corresponds to a temperature change of $\sim$20 K at 0.5 μbar, which is consistent with the temperature changes predicted by the Yates et al. model.

Subsequently, we fixed the temperature profile (as shown in Supplementary Figure 3) and adjusted the vertical profile of CH_4 near its homopause (see Supplementary Figure 5). With respect to the Moses et al., 2005[25] 'model A' vertical profile of CH_4, the position of its homopause would need to be moved upwards by greater than a pressure scale-height in altitude ($\sim$25-30 km) in order to yield a 3-4 K observed brightness temperature changes in time. At the 0.2-μbar level, this would correspond to a partial pressure or volume mixing ratio increase of $\sim 10^{-4}$. In solving the vertical continuity equation assuming the change in volume mixing ratio is driven entirely by upwards advection and not a chemical source (i.e. $w = (-\Delta X/\Delta t)/(\Delta X/\Delta z)$, where w is the vertical velocity, X is the volume mixing ratio, t is time and z is height), a change in vertical wind of 2.7 cm s^{-1} with respect to the steady state would be required. The Bougher et al., 2005 thermospheric model[26] predicts vertical winds at $\sim$70°S of approximately 50 cm s^{-1} at the 0.2 μbar level in steady state and thus a change in vertical wind of 2.7 cm s^{-1} is reasonable. We note a recent analysis, which compared *in-situ* Juno data and remote Hisaki observations, and found the consistency between datasets was optimized when the hydrocarbons (including CH_4) were allowed to be transported to higher altitudes[30].

Non-LTE effects are also likely important at the altitudes where the source of variability has been inferred and/or could itself be the driver of the observed variability. In the absence of a strong radiation source, 'classical' non-LTE effects become non-negligible at pressures lower than 0.1 mbar, where collisional timescales become longer than the spontaneous radiative lifetime[31,32]. Without a sufficient number of thermal collisions, a molecule's external energy and internal vibrational energies can go into disequilibrium and thus, the population of excited states is no longer Boltzmann-like (set by the gas temperature[32]) and the source function is no longer a Planck function. Appleby, 1990[31] predict the source-to-planck function ratio to be $\sim$0.8 at 10 μbar, dropping below 0.5 at pressures lower than 1 μbar. In comparison to non-auroral regions, the upper stratospheric heating present in Jupiter's auroral regions[6,10,33] also yields a larger contribution of photons at mid-infrared wavelengths from pressure levels where classical non-LTE processes become non-negligible. In addition to classical non-LTE processes, Jupiter's auroral regions are subject to further processes, which may induce a non-Boltzmann population of energy states[32]. This includes the excitation or de-excitation of CH_4 molecules by charged particle collisions and dissociative recombination processes, which occur at increased rates in Jupiter's auroral regions due to the influx electrons and other energetic particles. A further process might be 'H_3^+-shine', where the downward flux of H_3^+ emission in lines in the 3 - 4 μm range 'pump' overlapping CH_4 ν_3 lines, exciting the vibrational modes and thereby modifying the population of lines responsible for the ν_4 CH_4 band at $\sim$7.8 μm Modeling of the aforementioned non-LTE processes will be the subject of future work.

We cannot distinguish between temperature, abundance or non-LTE effects in driving the variable CH_4 emission observed between January 11-12th 2017. Nevertheless, either of these processes describes a direct coupling of the neutral stratosphere in Jupiter's auroral regions to the external magnetosphere of Jupiter. While daily variability of the northern auroral C_2H_4 and C_2H_6 emission have been observed in previous studies[4,34], we believe the results presented in this work represent a significant advance in understanding of this phenomenon. Firstly, the availability of high-resolution solar wind measurements and their propagation to Jupiter's orbit allowed the variability of the stratospheric CH_4 emission to be tentatively linked to external solar wind conditions and their perturbing effect on the magnetosphere. Secondly, COMICS imaging at high-diffraction limited spatial resolutions have allowed the morphology of the CH_4 emission and its variability to be resolved at finer spatial details. Using ionosphere-to-magnetosphere mapping calculations, this allowed the source of the strongest CH_4 emission and its variability to be mapped to the outer magnetosphere/magnetopause region. As demonstrated in previous work[6,10,33], auroral processes dominate the forcing of the thermal structure and chemistry at Jupiter's poles and the work in this paper demonstrates these processes are directly connected to the external magnetosphere. This phenomenon therefore could be ubiquitous for rapidly-rotating Jupiter-like exoplanets with an internal plasma source around a magnetically-active star[35]. In particular, MHD (magnetohydrodynamic) simulations of a hot-Jupiter at close orbital separations of 0.05 AU from its host star predict auroral powers of several orders of magnitude larger than on Earth and to affect both polar and equatorial regions[36,37]. The coupling of the neutral stratosphere and magnetosphere of Jupiter presented in this work may therefore be a process of importance in the near-future characterization of Jupiter-like exoplanets from the James Webb Space Telescope.

Methods

COMICS 7.8-μm images The COMICS (the COoled Mid-Infrared Camera and Spectrograph[7,12]) instrument is mounted at the Cassegrain focus of the Subaru Telescope, which is located at the Mauna Kea Observatory (approximately 4.2 km above sea level). Subaru's 8-metre primary aperture provides a diffraction-limited spatial resolution of ∼0.25" at 7.8 μm, which corresponds to a latitude-longitude footprint of approximately 2.5° x 2° at ±70° in latitude. COMICS provides both imaging and spectroscopic capabilities over a spectral range of approximately 7 to 25 μm. Images are measured on a 320 x 240 array of Si:As BIB (blocked impurity band) pixels each with a scale of 0.13”, which provides a total field-of-view (FOV) of 42” x 32”. Images can be measured over a number of discrete filters in both the N band (7 to 13 μm) and Q band (17 to 25 μm). In this work, we focus on images obtained in the 7.8-μm filter, which is sensitive to Jupiter’s stratospheric CH_4 emission (Supplementary Figure 2). Images were measured on January 11-14, February 4-5 and May 17-20 2017 (UTC). Measurements were performed during periods when Jupiter was available at airmasses lower than 3. The full disk of Jupiter (with equatorial diameters of ∼36” in January, ∼39” in February and ∼42” in May) could not be measured in a single image by the COMICS field-of-view (FOV). In January and February measurements, the full disk of Jupiter was measured using a 2 x 1 mosaic of individual images centred at Jupiter’s mid-northern and mid-southern latitudes. In May, a 2 x 2 mosaic was conducted due to Jupiter’s larger size during this time period. For each individual image, A-frames (of Jupiter) and B-frames (dark sky 60” north of Jupiter) were continuously recorded over a total exposure time of 20 seconds. Further details of the measurements presented in this work are provided in Supplementary Table 1.

Imaging processing, calibration and error handling Images were processed and calibrated using the Data Reduction Manager (DRM). A-B subtraction was performed to remove telluric sky emission. The resulting images were then divided by a ‘bad pixel mask’ accounting for corrupted pixels (due to cosmic ray damage, bright star saturation, manufacturer flaws etc.) and a flatfield in order to remove variations in pixel-to-pixel sensitivity across the detector. A limb-fitting procedure was used to assign latitudes, longitudes and local zenith angles to each pixel on the disk of Jupiter, using the known sub-observer latitude and longitudes at the time of each exposure. The absolute radiometric calibration of the images was conducted by scaling the observed lower latitude zonal mean brightness to those measured by Cassini's CIRS[38] instrument during the 2001 flyby. This procedure is described in greater detail in Fletcher et al., 2009[39]. We chose this method since experience with similar observations of Jupiter and Saturn has demonstrated that the radiometric calibration using a standard star provides inconsistency between datasets obtained on different nights[39,40]. Portions of the image within 6 pixels (or approximately 0.8") of the assigned limb were removed as a conservative means of removing the effects of seeing and diffraction in blurring dark sky together with emission from Jupiter. The noise-equivalent spectral radiance (NESR) was calculated by finding the standard deviation emission of dark-sky pixels more than 1.5" (or approximately 12 pixels) away from the planet. This was calculated for each image to capture changes in sensitivity due to variations in airmass and telluric atmospheric conditions between measurements. A centre-to-limb variation correction in the longitudinal direction was applied to correct for the foreshortening and limb-brightening such that longitudes at different viewing geometries on different nights could be more readily compared. A power-law fit, of the form $\log R = a \log \mu + b$, where R is radiance, $\mu = \cos\theta$ and θ is the zenith emission angle, was performed in each latitude band in order to derive a centre-to-limb correction factor. For January and February measurements, we performed the power-law correction using the January 11th 15:50 UT image (Figure 2a) in the southern hemisphere and the January 13th 12:30 UT image (Figure 3b) in the northern hemisphere. These specific images were chosen since they best capture non-auroral longitudes in each hemisphere. For May measurements, the May 17th 09:40 UT and May 18 09:35 UT images (Figures 1i, j) were similarly chosen to perform the power-law correction in the northern and southern hemispheres respectively.

Ionosphere to magnetosphere mapping We adopted the magnetosphere-ionosphere mapping calculation by Vogt et al.[14,15] to map a location on the planet in planetocentric latitude and system III longitude to its position in radial distance and local time in the jovian magnetosphere. The calculation is performed by imposing magnetic flux equivalence of a specified region at the equator to the area at which it maps in the ionosphere assuming a given internal field model. For this work, we adopted the VIPAL (Voyager Io Pioneer Anomaly Longitude) internal field model[41] due to its validity in both the northern and southern hemispheres and to larger (∼95 R_J) radial distances. Stepping through latitude and longitude in increments of 1° poleward of ±45° in latitude, the ionosphere-to-magnetosphere mapping calculation was performed to derive the local time and distance within the magnetosphere at each location. Regions enclosed within the statistical ultraviolet oval for which the calculation did not produce a real value were interpreted as mapping beyond the 95 R_J limit of the model, which also marks the estimated position of the dayside magnetopause[16]. This calculation was used to derive the contours shown in Figure 4.

Auroral-quiescent residual calculations Figure 4 demonstrates the areas denoted by 'Region A' and 'Region L' at both high-northern and high-southern latitudes. Region A (for 'auroral') was chosen as a sub-region of the auroral regions that was commonly sampled by all measurements presented in Figures 2 and 3. Region L was chosen as a lower latitude region away from the area of auroral influence, which is sampled at $\mu = cos(\theta_{emm})$ (where θ_{emm} is the zenith emission angle on Jupiter) in the range $0.4 < \mu < 1$. By calculating the residual between Region A and Region L, any inconsistencies in the radiometric calibration from one night to the next are effectively removed, which would otherwise affect a comparison of the absolute radiance in time. The mean radiances within Region A and Region L were calculated. The 1-σ uncertainty on the mean radiance in each region was chosen to be the larger of: 1) the NESR of each image (see Imaging processing, calibration and error handling) scaled by $1/\sqrt{n_p}$ where n_p is the number of pixels averaged or 2) the standard deviation on the mean radiance in the region. The radiances and uncertainties were then converted to brightness temperature units and the brightness temperature residual and uncertainty were calculated.

Solar-wind propagation model The Juno spacecraft continues to provide information on the magnetic and charged particle fields whilst performing 53.5 day orbits inside Jupiter's magnetosphere. However, the Juno spacecraft cannot provide *in-situ* measurements of the external solar conditions outside Jupiter's magnetosphere. In the absence of such measurements, we look instead to modelling results. A solar-wind propagation model[19] was adopted to calculate the solar-wind dynamical pressure ($p_{dyn} = \rho v^2$, where ρ is the density and v is the velocity of the solar-wind) impinging on Jupiter's magnetosphere. This model is used extensively by the outer planets magnetosphere community[42–44] in the absence of in-situ measurements of the solar-wind conditions. The model adopts hourly-resolution measurements of the solar-wind and magnetic field at Earth's bow-shock nose from OMNI[45] as input and then performs 1-D magnetohydrodynamic calculations to model the solar-wind flow out to Jupiter's bow-shock. The 1D model prediction of a 3D problem can introduce uncertainties on the arrival time and magnitude of dynamical pressure of solar wind compressions . When the Earth-Sun-Jupiter angle is less than ±50°, the uncertainty of the arrival time of the solar wind shock is less than ±20 h and that of the maximum dynamic pressure is 38%[21]. Given Earth-Sun-Jupiter angles were between 80 - 120° in the January-February 2017 time range, we adopted a 48-hour time error on the solar wind propagation model results. In May 2017, the Earth-Sun-Jupiter angle was approximately 18° and thus we assumed a time error of 20 hours in the May time range. These values also appear commensurate with a statistical comparison of 1D MHD predictions and solar wind data measured by several spacecraft[46]. The aforementioned error values are shown in Figure 5 to highlight the potential error to the reader.

Nemesis forward model calculations The NEMESIS forward model and retrieval tool[24] was adopted to perform forward model calculations of the 7.8-μm brightness temperature. A range of vertical profiles of temperature and CH_4 were forward modelled at different viewing geometries to test what type and magnitude of changes to these parameters could yield the observed temperature changes in time shown in Figures 2, 3 and 4. Forward model spectra were computed using the line-by-line method using the sources of line information for CH_4, CH_3D and $^{13}CH_4$, C_2H_2, C_2H_6, NH_3 and PH_3 detailed in Table 2 of Fletcher et al., 2012[47]. Calculations were performed using a square instrument function with a width of 0.04 cm^{-1} (chosen based on a balance of a sufficiently high spectral resolution to resolve both weak and strong emission line whilst minimising the number of spectral points to forward model) and subsequently convolved with the COMICS 7.8-μm bandpass and the telluric transmission spectrum (see Supplementary Figure 2). Specific calculations are detailed in Supplemental Information.

Code availability The Data Reduction Manager is a suite of IDL software designed for reduction and processing of planetary images and is available in compressed format from co-author, Orton, upon request (glenn.s.orton@jpl.caltech.edu). The ionosphere-to-magnetosphere mapping calculation is also written in IDL and is available from co-author, Vogt (mvogt@bu.edu), upon request.

Results of the solar wind propagation model in a specific time period may be requested from co-author, Tao (chihiro.tao@nict.go.jp), upon request. The NEMESIS forward model and retrieval tool is written in Fortran and is available as a GitHub repository: a user account for this repository may be requested from co-author, Irwin (patrick.irwin@physics.ox.ac.uk).

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Data Availability The COMICS images presented in this work will become publically-available on the SMOKA (Subaru Mitaka Okayama-Kiso Archive System, https://smoka.nao.ac.jp/) following a proprietary period of 18 months after measurement. Images still within their proprietary period may be requested from the principal investigator of the awarded telescope time (see Acknowledgements).

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