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### Identification of Jupiter's magnetic equator through H3+ ionospheric emission

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1                   **Identification of Jupiter's magnetic equator within H<sub>3</sub><sup>+</sup>**  
2   **ionospheric emission**

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18  
19 *May 31, 2018*

20

21 **Abstract:**

22

23 **Our understanding of Jupiter’s magnetic field has been developed through a**  
24 **combination of spacecraft measurements at distances  $>1.8 R_J$  and images of the**  
25 **aurora (1–7). These models all agree on the strength and direction of the jovian**  
26 **dipole magnetic moments, but, because higher order magnetic moments decay**  
27 **more strongly with distance from the planet, past spacecraft measurements could**  
28 **not easily resolve them. In the past two years, the Juno mission has measured**  
29 **very close to the planet ( $>1.05 R_J$ ), observing a strongly enhanced localized**  
30 **magnetic field in some orbits (8-9) and resulting in models that identify strong**  
31 **hemispheric asymmetries at mid-to-high latitudes (10, 11). These features could**  
32 **be better resolved by identifying changes in ionospheric density caused by**  
33 **interactions with the magnetic field, but past observations have been unable to**  
34 **spatially resolve such features (12–14). In this study, we identify a dark**  
35 **sinusoidal ribbon of weakened  $H_3^+$  emission near the jovigraphic equator, which**  
36 **we show to be an ionospheric signature of Jupiter’s magnetic equator. We also**  
37 **observe complex structures in Jupiter’s mid-latitude ionosphere, including one**  
38 **dark spot that is coincident with a localized enhancement in Jupiter’s radial**  
39 **magnetic field observed recently by Juno (10). These features reveal evidence of**  
40 **complex localized interactions between Jupiter’s ionosphere and its magnetic**  
41 **field. Our results provide ground-truth for Juno spacecraft observations and**  
42 **future ionospheric and magnetic field models.**

43

44

45

46 The NASA InfraRed Telescope Facility observed Jupiter over a period of 48 nights  
47 between 1995-2000, using the NSFCam instrument (15) to take images at  
48 wavelengths of 3.42-3.46 and 3.53 microns in order to measure emission from the  
49 ionic molecule  $\text{H}_3^+$ , a dominant ion in Jupiter's upper atmosphere. These filters  
50 include light from the lower atmosphere that cannot be removed from individual  
51 images, preventing an accurate measure of ionospheric emission. Here, instead of  
52 measuring the ionosphere on an individual night, we produce a measure of the mean  
53  $\text{H}_3^+$  ionospheric emission over a period of several years. Any magnetically induced  
54 density changes will consistently appear at the same SIII latitude and longitude and,  
55 since Jupiter's upper atmosphere broadly co-rotates with the magnetic field (16), any  
56 magnetically forced temperature differences will also be broadly fixed in SIII (17).  
57 Jupiter's troposphere, however, rotates at a different rate to the magnetic field, and so  
58 it is possible to isolate ionospheric density differences caused by the magnetic field by  
59 observing the ionosphere over an extended period of at least several months, so that  
60 the rotational phase of the underlying neutral atmosphere is completely de-coupled  
61 from the SIII longitudinal system (18). If tropospheric weather features move with a  
62 velocity of order 100 m/s in SIII, in ~50 days these features would complete one full  
63 rotation around the planet. Equatorial observations are further complicated by the  
64 recent discovery that ionospheric emissions are enhanced above the Great Red Spot  
65 (19), through an as-yet unknown process, but such processes are again coupled to  
66 Jupiter's lower atmosphere. This means that brightness changes associated with the  
67 underlying troposphere can be removed from the average image brightness observed  
68 over five years, using a process described in the Methods section, resulting in a map  
69 that highlights any spatial differences in Jupiter's  $\text{H}_3^+$  emission, completely de-  
70 coupled from the troposphere.

71

72 This map, shown in Figure 1, reveals both large- and small-scale non-auroral emission  
73 structures. Since  $H_3^+$  brightness is driven by both  $H_3^+$  density (which controls the  
74 emission through the number of emitting molecules per unit volume) and  
75 thermosphere temperature (which determines the energy emitted per  $H_3^+$  molecule),  
76 and since the image filter includes emission from multiple lines of  $H_3^+$ , we cannot  
77 measure absolute line brightness. Instead we compare the brightness of features with  
78 the brightest auroral feature observed across all longitudes between  $75^\circ N$  and  $75^\circ S$ ,  
79 designated here as the peak Main Auroral Brightness (MAB). The measured average  
80 brightness between  $35^\circ N$  and  $35^\circ S$  is 7.34% MAB.

81

82 At the largest scales, there are two ionospheric regions that appear darker: a longitude  
83 band between about  $30^\circ$ - $150^\circ W$  with localized patches of darkness, concentrated in  
84 the northern hemisphere, where emission drops as low as 5.5% MAB; and a region of  
85 weaker darkening at longitudes between  $180^\circ$ - $270^\circ W$ , extending across the southern  
86 hemisphere and as far as  $\sim 10^\circ N$ , where emissions are  $\sim 6.5$ - $7\%$  MAB. These two  
87 darker regions are surrounded by brighter regions where emissions are  $>7.5\%$  MAB.  
88 The first of these darker regions has previously been identified, but at spatial scales  
89 too large to resolve any of the small-scale features we observe here (13, 14). This  
90 region is co-incident with a region of enhanced neutral atmospheric emission named  
91 the 'Lyman- $\alpha$  bulge' that has previously been inferred to be associated with the  
92 decrease in the  $H_3^+$  density through electron recombination (20). No Lyman- $\alpha$   
93 observations have been obtained at the spatial resolution required to identify small-  
94 scale structures.

95

96 One of the most prominent small-scale ionospheric features is a darkened ‘ribbon’ of  
97 weak emission that appears to undulate with an approximately sinusoidal form within  
98 about 15° of the jovigraphic equator, roughly following the path of the northern and  
99 southern auroral oval limits. This ribbon has its lowest intensity at 20°N, 90°W and  
100 15°S, 220°W, where emission drops as low as 5.5% MAB, but forms a continuing  
101 narrow ribbon of lowered emission across most longitudes. This feature is observed in  
102 each of the H<sub>3</sub><sup>+</sup> filters used in the study, as shown in the supplemental information.

103

104 Past ionospheric modelling has suggested that localized equatorial H<sub>3</sub><sup>+</sup> densities  
105 should be directly affected by Jupiter’s magnetic field (21). Photoelectrons, electrons  
106 produced through the photoionization of a neutral particle, play an important role in  
107 the creation of H<sub>3</sub><sup>+</sup>. In the jovian upper atmosphere, collisions between  
108 photoelectrons and H<sub>2</sub> are a significant source of H<sub>3</sub><sup>+</sup>. Because photoelectrons  
109 preferentially travel along magnetic field lines, the horizontal orientation of the field  
110 lines at the magnetic equator diverts photoelectrons to higher latitudes as they move  
111 to lower altitudes. This mechanism thus reduces the H<sub>3</sub><sup>+</sup> column production rate in the  
112 vicinity of the magnetic equator. Current modelling is too spatially coarse to fully  
113 resolve this effect, but suggests that the corresponding H<sub>3</sub><sup>+</sup> density is reduced by at  
114 least 1-2% within ~10° of the jovimagnetic equator (21).

115

116 The observed H<sub>3</sub><sup>+</sup> emission in this region is consistent with this process, although the  
117 observed reduction in brightness is larger than predicted. Deflected photoelectrons  
118 should also slightly enhance the photoelectron density immediately poleward of the  
119 magnetic equator, potentially explaining the small enhancement in H<sub>3</sub><sup>+</sup> emission in  
120 this region. Since the sinusoidal morphology of the darkened ribbon is difficult to

121 explain as a stable thermospheric cooling structure, the dark ribbon is most likely  
122 caused by a reduction in the local  $\text{H}_3^+$  density, strongly suggesting that it demarcates  
123 the location of the jovimagnetic equator. We considered the possibility that the dark  
124 ribbon and flanking features were caused by an alternative ionospheric process, such  
125 as the ‘fountain effect’ similar to that which produces Earth’s Equatorial Ionization  
126 Anomaly (22). However, this transport-driven process only shapes the terrestrial F  
127 region and does not influence lower altitude layers that are dominated by chemistry.  
128 Since the  $\text{H}_3^+$  emission peak at Jupiter is in photochemical equilibrium (21), it is  
129 improbable that the  $\text{H}_3^+$  density depletion is shaped by a similar fountain process.  
130  
131 To find the position of the dark ribbon, we averaged the emission intensity over  $10^\circ$   
132 longitudinal bins between  $20^\circ\text{N}$  and  $20^\circ\text{S}$ , fitting the selected data with a negative  
133 Gaussian profile of brightness as a function of latitude. These positions are identified  
134 in the bottom-left panel of Figure 1 (yellow crosses) and are listed in Table 1. We  
135 then averaged the  $\text{H}_3^+$  emission across all longitudes against distance from the dark  
136 ribbon and plotted this average emission against distance (shown in the bottom right  
137 panel of Figure 1). This latitudinal profile has a significant decrease of  $\sim 0.8\%$  MAB at  
138 its centre ( $\sim 12\%$  of the non-auroral brightness) and increases with latitude on either  
139 side of the dark ribbon, such that the mean non-auroral level of emission is attained at  
140 locations about  $10^\circ$  away from the centre. This is surrounded by a slight, localized  
141 brightening of  $\sim 0.1\%$  MAB ( $\sim 1.5\%$  of the non-auroral brightness)  $20^\circ$  either side of  
142 the dark ribbon’s centre.  
143  
144 Further support for the dark ribbon marking the location of the jovimagnetic equator  
145 comes from the observed location of the jovian H Lyman- $\alpha$  bulge, theorised to be

146 offset from the jovigraphic equator as a result of magnetic field distortions (20). The  
147 calculated peak UV emission latitudes, shown in Figure 2 by the blue-dashed line,  
148 overlaps with the location of the dark ribbon within the errors of both measurements.

149

150 As discussed previously, the recently published JRM09 model (11) now provides a 10  
151 degree spherical harmonic model of Jupiter's magnetic field. In Figure 2 we compare  
152 the smoothed location of the dark ribbon with the modelled magnetic particle drift  
153 equator calculated from the JRM09 model. The inferred magnetic equator follows the  
154 modelled magnetic equator very closely across most longitudes and is typically  
155 located within  $\pm 5^\circ$  of the spacecraft derived magnetic equator. The only location  
156 where the magnetic field is not co-located is in the 0-60°W range, where the  
157 darkening at the equator is particularly weak. The close alignment of the dark ribbon  
158 and the JRM09 equator strongly suggests that the dark ribbon is an ionospheric  
159 feature that is directly associated with the magnetic field lines that uniquely run  
160 parallel to the surface at Jupiter's magnetic equator. It also suggests that the location  
161 of Jupiter's magnetic equator has remained stable over the over the 15 years  
162 separating these two independent measurements.

163

164 Away from the equatorial regions, our observations show significant local brightness  
165 changes. In the 60-140°W region we observe a longitudinally broad darkening (5.5%  
166 MAB) at  $\sim 40^\circ$ N (poleward of the dark ribbon) and a narrow dark spot (6% MAB)  
167 focused on 25°S, 90°W. In addition, two dark arcs (7% MAB) are visible at 25°-40°N  
168 and  $\sim 60^\circ$ N between 270° and 330°W, within a broad region of raised emission (about  
169 8-10% MAB).

170



171 These localized dark regions could result from either lower ion density or a localized  
172 region of cooling. The most poleward arc, at  $\sim 60^\circ\text{N}$  and around  $300^\circ\text{W}$  was recently  
173 identified as a ‘Great Cold Spot’ in Jupiter’s thermosphere, where local temperatures  
174 are  $\sim 150\text{ K}$  cooler than the surroundings (17). None of the other features identified  
175 here have previously been observed.

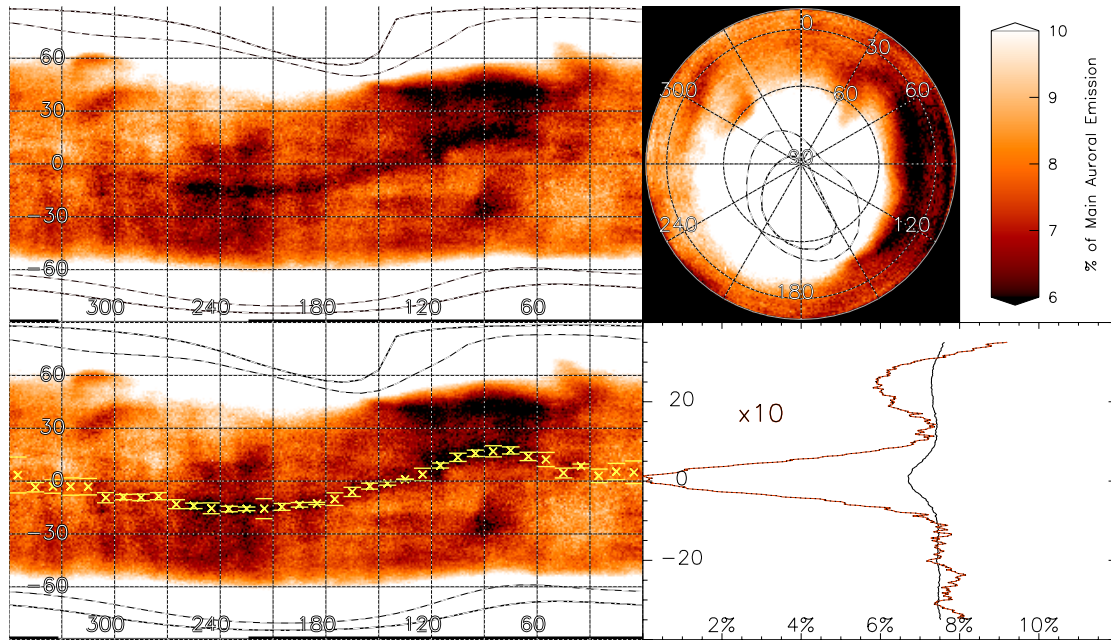
176

177 While a detailed modelling of Jupiter’s magnetic field awaits more orbits from Juno,  
178 magnetic measurements from the first perijove pass (PJ1) revealed that Jupiter’s  
179 radial field appears to be enhanced by a factor of two on field lines that map to  $30^\circ$ -  
180  $45^\circ\text{N}$  and  $90^\circ\text{W}$  (10). This region is directly aligned with the strongest darkening in  
181 our ionospheric emission maps. If future spectral observations reveal that this dark  
182 region is caused by decreased density, this strongly suggests lower precipitating  
183 electron flux from the magnetosphere in this region, due to the localized enhancement  
184 in the magnetic field strength; this would be the inverse of the enhanced ionosphere  
185 observed in Earth’s South Atlantic anomaly, where the magnetic field strength is a  
186 local minimum.

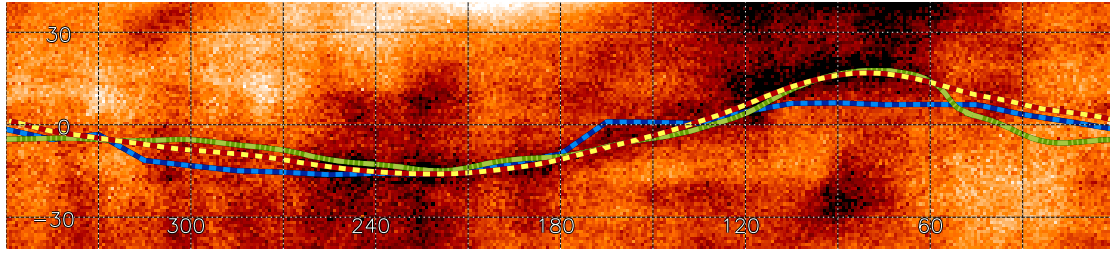
187

188 Detailed ionospheric modelling, combined with follow-up spectral observations, will  
189 allow us to test what ionospheric process drives the darkening of  $\text{H}_3^+$  at Jupiter’s  
190 jovimagnetic particle drift equator, providing us with new insights into Jupiter’s  
191 equatorial ionosphere. The continuing magnetic measurements made by Juno will  
192 allow us to further assess whether or not the mid-latitude localized dark regions are  
193 driven by Jupiter’s localized magnetic structure. If this is the case, we have  
194 discovered an alternative measure of Jupiter’s magnetic field at a comparable spatial  
195 scale to the longitudinal gaps between the planned orbits of Juno, providing a ground-

196 truth for the Juno magnetometer dataset. With a two-decade gap in observation and  
 197 the potential for ongoing monitoring into the future, this may allow us to reveal the  
 198 rate of change in Jupiter's complex mid-latitude magnetic field, thus providing new  
 199 insight into Jupiter's internal processes.  
 200



201  
 202 Figure 1:  $H_3^+$  ionospheric emission at wavelengths of 3.42-3.46 and 3.53 micron. The  
 203 top-left panel shows a cylindrical map of the square root of the MAB-scaled equatorial  
 204  $H_3^+$  emission (see text), scaled between 6% and 10% of MAB, and the top-right panel  
 205 shows the same map in northern polar orthographic projection. The location of the main  
 206 auroral emission (black and white dot-dashed line) and Io spot and trail (black and white  
 207 dashed line) are taken from the Grodent et al (2008) model. The bottom-left panel  
 208 shows the same map, overlain by the calculated positions of the dark ribbon from Table  
 209 1 (yellow-crosses), bounded by the standard-deviation error of these fitted positions  
 210 (yellow lines). The bottom-right panel shows the latitudinal profile of emission  $35^\circ$   
 211 either side of the fitted dark ribbon position averaged over all longitudes (black line).  
 212 This is also shown scaled by a factor of 10, for clarity (red).



213

214 Figure 2: Equatorial magnetic field mapping. Here, we show the same cylindrical map

215 of equatorial H<sub>3</sub><sup>+</sup> emission in Figure 1, with the same scaling, from 40°N to 40°S.

216 Overlain on this are: a rolling 13-element cubic fit of the dark ribbon positions (red-

217 yellow dashed line); the central positions of the UV H Ly-α emission (20; blue dashed

218 line); and the JRM09 magnetic field model particle drift equator, where the magnetic

219 field lines are parallel to Jupiter's 'surface' (11; light green four-dash line).

220

West longitude (degrees)	Latitude (degrees)	Latitude error (degrees)
0-10	5.0	6.5
10-20	5.4	4.6
20-30	3.0	4.2
30-40	8.6	1.0
40-50	4.6	3.0
50-60	12.3	4.2
60-70	14.0	2.0
70-80	17.4	1.4
80-90	16.9	2.8
90-100	15.8	1.5
100-110	13.5	2.5
110-120	8.8	0.9
120-130	4.6	3.3
130-140	1.0	0.2
140-150	-1.3	1.4
150-160	-2.9	1.4
160-170	-6.2	2.7
170-180	-10.2	2.9
180-190	-12.7	0.3
190-200	-13.5	1.3
200-210	-14.7	1.0
210-220	-15.7	6.3
220-230	-15.8	1.2
230-240	-15.8	1.5
240-250	-15.5	2.9
250-260	-14.1	1.6
260-270	-13.1	3.0
270-280	-8.6	1.7
280-290	-9.3	1.5
290-300	-9.1	1.3
300-310	-9.5	3.0

310-320	-3.2	4.1
320-330	-3.1	4.4
330-340	-3.1	3.9
340-350	-3.5	2.7
350-360	3.4	10.1

221

222 Table 1: The calculated position of the dark ribbon (a proxy for the jovian magnetic  
 223 equator). The latitudes shown were calculated by binning emission between 20°N and  
 224 20°S in 10-degree longitude bins and fitting a minimum Gaussian peak.

225

226

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307

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322

323 **Individual contributions:**

324 T.S.S. Project leader, data reduction, data analysis, figure production, paper writing

325 A.G.B. Equatorial modelling for Earth comparison, detailed discussions, writing for  
326 magnetic field interactions, general corrections

327 H.M. Data analysis: image processing and limb fitting techniques, general corrections

328 L.N.F. Data analysis: tropospheric emission, discussion of troposphere, general  
329 corrections

330 S.M. Discussion of data analysis techniques, general corrections

331 L.M. Detailed discussions of Jupiter's ionosphere, writing for ionosphere, general  
332 corrections



333 J.O. Discussion of ionospheric darkening, general corrections  
334 J.E.P.C. Project leader on original observations, data reduction, detailed discussions  
335 of magnetic field modelling, general corrections  
336 T.S. Observer, detailed discussion of instrumental errors, lead discussion on testing of  
337 image processing technique, general corrections  
338 R.E.J. Discussion of data analysis techniques, general corrections

339

340

## 341 **Methods**

### 342 **Introduction**

343 This study uses 13,501 images of  $H_3^+$  emission taken over 48 nights between 1995  
344 and 2000 (23). These images were taken using the NSFCam instrument at the NASA  
345 InfraRed Telescope Facility (15) using a range of filters that cover the 3.4-3.6 micron  
346 range, starting from the sky-subtracted and flat-fielded images produced for the  
347 ‘Magnetospheres of the Outer Planets Infrared Data Archive’. These observations are  
348 described in detail within the supplementary information of Stallard et al., 2017 (17),  
349 along with a full description of the initial reduction technique used for these images.  
350 Here, we briefly describe these techniques and then detail the additional techniques  
351 that are unique to this paper.

352 The ‘Magnetospheres of the Outer Planets Infrared Data Archive’ provides two kinds  
353 of image, individual flat-fielded and sky subtracted images and ‘reduced’ combined  
354 data, where individual images have been stacked together. In order to properly

355 remove bad data and provide an accurate limb fit, we use the former individual  
356 images.

357 These images consist of a range of different wavelength settings, focused on  
358 wavelengths with  $H_3^+$  emission, with earlier observations using the NSFCam CWF  
359 centered on three different wavelengths, 3.420, 3.430 and 3.460 micron, with a  
360 spectral resolution of  $\sim 50$  and later images utilizing two very narrow fixed filters with  
361 a central wavelength of 3.4265 and 3.542 micron and a spectral resolution of 200. The  
362 precise filter distributions for each of these settings is not well known, so we are  
363 unable to produce precise values for  $H_3^+$  line intensity. Instead, we measure the peak  
364 auroral brightness between  $75^\circ N$  and  $75^\circ S$  (avoiding the poles to remove errors in  
365 line-of-sight correction) for each individual filter and use this to scale the non-auroral  
366 filter emission.

367 Internal reflections within the NSFCam imager cause a rotated and reversed image to  
368 appear within the data as a 'ghost'. The brightness of this ghost varies significantly,  
369 depending upon unknown factors, most likely instrument illumination angles. This  
370 results in a 'ghost' image with a brightness of 0.001-0.05 of the primary signal. As a  
371 result, subtracting the signal is difficult, and instead, we mask this signal out  
372 completely, removing a region of the image brighter than our threshold, set to 17.5 in  
373 our raw data (before main auroral brightening is scaled for), as well as  $\pm 40$  pixels in  
374 both x and y around the center of any bright moon within the image. This results in a  
375 blanked out region within each region, which can be seen in Supplementary Figure 1  
376 as two black regions (a square in one corner and a curved image) at the bottom of the  
377 image. Data in this region is ignored in our mapping. Again, this process is described

378 in more detail in the supplementary information for Stallard et al., 2017 (17), and is  
379 tested within the supplementary information for this paper.

380 We then fit the center of the planet within each image using a by-eye limb fitting  
381 technique. We estimate that this resulted in a positional accuracy of  $<0.5''$ . In Stallard  
382 et al., 2017 (17), this planetary center is used to calculate the latitude and longitude  
383 for each corner of each pixel within each image that transects the planetary disk, and  
384 use this to map the data into a latitude and longitude grid, allowing us to combine  
385 every image into an average brightness map. We apply the same mapping here, but  
386 before mapping the data, we apply a line-of-sight correction, to correct for limb  
387 brightened  $H_3^+$ .

388

### 389 **Line-of-sight correction to images**

390 The  $H_3^+$  emission measured within an image is geometrically enhanced as a function  
391 of the apparent geometric position on the planetary disk, increasing towards the limb  
392 of the planet as a result of an increased depth of the radiating column of  $H_3^+$  observed.  
393 This geometric effect distorts emission from across the entire disk of the planet, but is  
394 clearest on the equatorial limb, since  $H_3^+$  emission in this region is uniformly  
395 generated by solar ionisation, yet the apparent brightness increases at the limb.  
396 Supplementary Figure 1a shows a clear limb enhancement within the auroral region,  
397 where the apparently brightest aurora is incident with the limb, with the non-auroral  
398 ionospheric emission also showing enhancement along the dusk limb down to  
399 equatorial regions.

400

401 We calculate a theoretical enhancement for the planetary geometry of each individual  
 402 image, as shown in Supplementary Figure 1b-i. The center of the planet has been  
 403 fitted for each image by-eye. Accounting for the equatorial diameter of the planet, the  
 404 flattening of Jupiter, and the sub-Earth latitude, this provides a ratio of the radial  
 405 distance of each pixel ( $r_x$ ), relative to both the center of the planet and the 1 bar limb  
 406 ( $r_1$ ). We then model emission as a uniform shell of emission 100km thick, positioned  
 407 at altitude of 400km ( $r_2$ ) and 500km ( $r_3$ ) above the 1 bar surface ( $r_1$ ). We model the  
 408 atmosphere as opaque below this 1 bar limb and transparent above it.

409

410 The enhancement is thus calculated as the geometric enhancement of emission  
 411 compared with the geometric center of the planet:

412

413 Below the limb ( $r_x < r_1$ ):  $\sqrt{r_3^2 - r_x^2} - \sqrt{r_2^2 - r_x^2}$

414 Below the  $H_3^+$  layer ( $r_1 < r_x < r_2$ ):  $2 \left[ \sqrt{r_3^2 - r_x^2} - \sqrt{r_2^2 - r_x^2} \right]$

415 Within the  $H_3^+$  layer ( $r_2 < r_x < r_3$ ):  $2 \sqrt{r_3^2 - r_x^2}$

416

417

418 This gives the idealised  $H_3^+$  enhancement for any position within the image, but since  
 419 we are observing Jupiter from Earth, the distorting effect of turbulence within Earth's  
 420 atmosphere, the 'seeing', will blur out this line-of-sight enhancement.

421

422 We have calculated the mean seeing for each night using star calibration images taken  
 423 on each night. We fit each individual star image with a Gaussian in four directions,  
 424  $0^\circ$ - $180^\circ$ ,  $45^\circ$ - $225^\circ$ ,  $90^\circ$ - $270^\circ$  and  $135^\circ$ - $315^\circ$  to produce an average full-width half-  
 425 maximum (FWHM) for each star image. The mean seeing is the average FWHM

426 across all the star images for each night. These are listed for each night in Stallard et  
427 al. (2017).

428

429 In order to calculate the seeing-convolved line-of-sight enhancement, we take the  
430 theoretical line-of-sight enhancement and convolve this using a 2D Gaussian with a  
431 FWHM of the nightly seeing. This results in a more realistic line-of-sight  
432 enhancement with which to correct our image, shown in Supplementary Figure 1b-ii,  
433 scaled to ensure that the correction at the geometric center of the planet is at unity.  
434 This more realistic line-of-sight enhancement is used to correct our data: dividing the  
435 image by this seeing-convolved line-of-sight converts the line-of-sight brightness to a  
436 vertical column-integrated, as shown in Supplementary Figure 1c.

437

### 438 **Removal of thermospheric emission**

439

440 Once the images have been mapped, we can measure the resultant time-averaged  
441 image brightness from Jupiter, shown in Supplementary Figure 2. This image still  
442 contains the longitudinally smoothed reflected sunlight from the troposphere and can  
443 be directly compared with the Figure 1 of the paper, which shows the same emission  
444 once this tropospheric background has been removed. Because the image filter  
445 settings used obscure the exact spectral characteristics of the  $H_3^+$  emission that  
446 dominates these images, we normalise the brightness of our maps to the brightest  
447 auroral emission equatorward of  $75^\circ$ . We refer to this emission level in the paper as  
448 the main auroral brightness (MAB). The top row of Supplementary Figure 2 shows a  
449 cylindrical projection of  $H_3^+$  emission alongside an orthographic polar projection,  
450 which shows the northern auroral region.

451

452 The bottom rows of Supplementary Figure 2 show this same cylindrical map in the  
453 first column, now scaled to enhance the non-auroral emission by scaling the emission  
454 intensity between 10% MAB and below 6% MAB, again with the color scale  
455 stretched by the square root. At this intensity level, the non-auroral intensity appears  
456 to be dominated by two bright bars that stretch across all longitudes at about 8°N and  
457 18°S. This emission does not coincide with ionospheric features in past spectral  
458 observations, but instead coincides approximately with observations of Jupiter's  
459 tropospheric emission (18), typically observed at longer wavelengths (*e.g.* 5.32  
460 microns). The exact locations of tropospheric bands vary significantly with  
461 wavelength, and tropospheric emission has not previously been measured at  
462 wavelengths as short as ~3.5 microns, so we cannot be sure of what are the expected  
463 morphology of these tropospheric regions, but the approximate location of the two  
464 bands is similar to that observed at 5 microns, as shown in the bottom right panel of  
465 Supplementary Figure 3. This emission appears to escape absorption in the  
466 stratosphere through narrow absorption gaps at about 3.44 and 3.52 microns,  
467 identified in standard Jupiter spectra taken from the IRTF spectral library (24).

468

469 Although tropospheric emissions are localized, they are also highly dynamic. Since  
470 the troposphere is generally fixed within Jupiter's System I and II coordinates, the  
471 emissions from these atmospheric storms and spots will have completely smeared out  
472 over the six-year period in the System III coordinates used to create this emission  
473 map, resulting in a longitudinally uniform tropospheric contribution that would not be  
474 significant in emission maps from a single night. In order to remove this non-  
475 ionospheric signal, we measure the longitudinally averaged map brightness, shown in

476 the bottom right panel of Supplementary Figure 2. We cannot be sure of the total  
477 brightness of this tropospheric contribution, but typical measures of this emission at  
478 other wavelengths (shown as the red dashed line) suggest that they are brightest at the  
479 equator, and are typically much weaker and smooth between  $28^{\circ}$ - $35^{\circ}$ N and  $25^{\circ}$ - $35^{\circ}$ S.  
480 Thus, we use these regions poleward of the equator (shown in blue in the bottom-right  
481 panel) to model the background emission (which consists of both tropospheric and  
482 ionospheric emission) a second-order polynomial (shown by the blue dashed line).  
483 Subtracting this background from the longitudinally averaged intensity profile  
484 provides us with a model of the longitudinally-smoothed tropospheric intensity.

485

486 The tropospheric background intensity model is not calibrated in absolute brightness,  
487 but does make it possible to produce a map of the relative brightness of  $H_3^+$  emissions.  
488 Because the tropospheric signal is longitudinally smoothed over the 48 nights of  
489 observation while most  $H_3^+$  emission structure is fixed to the magnetic field, only  $H_3^+$   
490 features that are associated with non-System III coordinates, such as the recent  
491 detection of bright  $H_3^+$  emission associated with the Great Red Spot (19), will be lost  
492 through this technique. It is also possible that the  $H_3^+$  emission brightness in the  
493 equatorial region has been over-estimated, due to an under-estimation of the  
494 tropospheric brightness – however, the location of ionospheric features (revealed by  
495 relative brightening and darkening) is well defined by this method.

496

### 497 **Identifying the location of the equatorial dark ribbon**

498 In order to measure the location of the dark ribbon that appears to follow Jupiter's  
499 magnetic equator, shown in Figure 1 of the paper, we fitted latitudinal profiles of the  
500 data, binned in longitude, with negative Gaussians. Firstly, we took the emission

501 between 20N and 20S and binned it into 10° longitude bins. This resulted in 36  
502 latitudinal profiles, shown in Supplementary Figure 3. We provided an initial  
503 estimated depth and location of the dark ribbon, in order to provide the fitting  
504 procedure with a starting Gaussian shape, then fitted each profile with a Gaussian and  
505 quadratic background – if the resultant fit produced a positive value, or a central  
506 position outside 20°N and 20°S, the values for the starting Gaussian shape were  
507 randomly changed until a fit within these constraints was found (this removed some  
508 instances where the Gaussian fitting procedure assumes the entire profile is part of the  
509 flank of the Gaussian, resulting in nonsensical dark ribbon positions). This fit  
510 provided an assessment of the noise level of the data once the Gaussian was  
511 accounted for. We then tested the errors in this fitted position by obtaining the  
512 calculated noise level from the original fit, and randomly regenerating the noise in the  
513 data, and refitting the data, a process that we repeated 1000 times. The standard  
514 deviation in the fitted positions across these 1000 fits was then calculated, to provide  
515 a measurement of the fitting error. The Gaussian position and fitting errors are  
516 described in Table 1 of the paper and are shown as yellow crosses and lines in the  
517 bottom panel of Figure 1 in the paper.

518

#### 519 **Additional Methods References**

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526

527 **Data Availability Statement**

528 The data used in this study was originally released as the Magnetospheres of the Outer

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530 <https://dataverse.harvard.edu/dataverse/h3p> and has the DOI:

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