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Infrared observations of Jovian aurora from Juno's first orbits: main oval and satellite footprints.

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Abstract.

The Jovian Infrared Auroral Mapper (JIRAM) is an imager/spectrometer on board NASA/Juno mission dedicated to the study of the Jovian aurorae.

Here we present the first results of JIRAM's observations of the H_3^+ infrared emission with the *L* band imager channel, collected around the first Juno perijove (August 2016). These observations provide excellent spatial and temporal distribution of the Jovian aurora. They show the morphology of the main oval, the polar region, and the footprints of Io, Europa and Ganymede.

The extended “tail” downstream of Io persists for almost 5 hours after the passage of the satellite flux tube. Multi-arc structures of varied spatial extent appear in both the northern and southern main auroral ovals. Inside the main oval, intense, localized emissions are observed. In the southern polar region, a very evident circular region characterized by a strong depletion of H_3^+ emissions is partially surrounded by an intense emission arc. The southern

39 aurora is brighter than the north one in these observations, but similar and probably conjugate
40 emission patterns are distinguishable in both polar regions.

41

42

43 Key points:

44 Tail of Io magnetic footprint longer than previously detected.

45 Identification of thin multiple arc structures in the northern and southern ovals, and of bright
46 spots and depletion in the south pole

47

48 Filamentation of alternatively upward and downward current in the 0° - 90° SIII sector in the
49 north;

50

51 **1 Introduction**

52 The Jovian Infrared Auroral Mapper (JIRAM, Adriani et al., 2008, 2014, 2016) is an imaging
53 spectrometer on board the Juno spacecraft, which started the prime mission around Jupiter on
54 August 2016 (Bolton et al., 2017).

55 The JIRAM investigation was purposely designed to explore the Jovian aurorae and the planet's
56 atmospheric structure, dynamics and composition. The main auroral oval emission is thought to
57 be associated with upward field-aligned currents driven by the breakdown of corotation
58 between the planet and the plasma sheet, partially supplied as neutral gas by Io's volcanic
59 activity. It has been suggested that such breakdown occurs at equatorial magnetospheric
60 distances from 15 to 40 RJ, and generates a global current system whose upward branch is
61 associated with auroral precipitation (Cowley and Bunce, 2001; Hill, 2001). Outside of the main
62 oval, signatures of electromagnetic interactions between Jupiter and its moons (particularly Io)
63 are present (Connerney et al., 1993).

64 Emissions poleward of the main auroral oval are thought be connected to the outer
65 magnetosphere, possibly related to a sector of the Dungey and Vasylunas cycle flows (Cowley et
66 al., 2003; Grodent et al., 2003). In the UV, this region shows the highest temporal and spatial
67 variability and this is where the largest differences in comparison to IR emission behaviors have
68 been observed (Radioti et al., 2013).

69 Emission due to the H_3^+ ion is prominently observable in the JIRAM spectral range. Its main
70 roto-vibrational band is around 2521 cm^{-1} , composed of more than 200 possible transitions in
71 the range $3.0\text{-}5.0\text{ }\mu\text{m}$; observation of the infrared emission of H_3^+ is mainly possible in a spectral
72 interval ($3.2\text{ to }4.0\text{ }\mu\text{m}$) where the solar and thermal radiance emitted by the planet are very low
73 due to the intense atmospheric methane absorption band, resulting in a high auroral contrast
74 against Jupiter's dark disk (Connerney and Satoh, 2000).

75 **2 Data set**

76 JIRAM combines two data channels (images and spectra) in one instrument. The optical design
77 uses a reflecting telescope and a grating spectrometer in Littrow configuration. Two distinct
78 focal plane detectors are used for imaging and spectroscopy. The aberrations in the telescope
79 and spectrograph optical path are corrected with dioptric doublets. The instrument uses a
80 dedicated de-spinning mirror to compensate for spacecraft rotation (1 or 2 rotations per
81 minute). The instrument is designed to perform one acquisition, consisting of two 2D images in
82 different spectral ranges/channels, and a 1D slit with full spectral resolution, every spacecraft
83 rotation (currently 30 s). JIRAM can tilt its field of view (FoV) above or below the sub-spacecraft
84 point, along the plane perpendicular to Juno spin axis, by delaying or anticipating the
85 acquisition, which by default is taken at nadir. JIRAM cannot articulate its FoV in any other
86 direction without turning the spacecraft.

87 The imager channel is a single detector (266×432 pixels) with two different filters (128×432
88 px each), separated by a 10-pixel wide, inactive strip. Of the two filters, one (*L* band, from 3.3 to
89 $3.6\text{ }\mu\text{m}$) is devoted to imaging H_3^+ emission and provides spatial context for the spectral
90 observations. The pixel angular resolution is 0.01° . The FoV of the *L* band is 5.87° by 1.74°
91 degrees. The spatial resolution, at the surface, varies with the spacecraft radial distance and it is

92 of the order of 100 km during most imaging activities. The other filter (*M* band, from 4.5 to 5
93 μm) is suitable for mapping the thermal structures of the atmosphere. Prior to observing
94 Jupiter, a general calibration campaign was performed, including an assessment of pointing
95 knowledge and accuracy and detector sensitivity, resulting in minor corrections of the pointing
96 knowledge and sensitivity, revised to $2 \times 10^6 \text{ counts s}^{-1} / (\text{W m}^{-2} \text{ sr}^{-1})$.

97 JIRAM took more than 4000 images and spectra (Adriani et al., 2017, Dinelli et al., 2017) of
98 Jupiter's aurorae and atmosphere prior to and immediately following the 1st Juno perijove pass
99 (Aug. 27th 2016). In particular, more than 600 images of the filter-integrated radiance in the *L*
100 band have been collected over the northern and southern aurorae, with an unprecedented
101 spatial resolution and vantage point.

102 The JIRAM FoV is not able to cover the entire polar region in a single image during Juno's
103 passage over the poles because the spacecraft is too close to Jupiter. However, JIRAM's field of
104 view can be articulated with the scanning mirror to scan across most of the auroral features.
105 These "tilted" images are organized in groups ("scans") of ~ 25 images each. Each image is a 1
106 second integration; images are acquired 30 seconds apart, so that a complete scan takes ~ 12
107 minutes to be performed. The resulting mosaic gives a comprehensive image of the aurora, and
108 satellite footprints visible within the imaged area. Mosaics are assembled by processing the data
109 to remove contamination (see section 3) and averaging the best available imagery where
110 images overlap.

111 The northern aurora was observed from 08:24 to 11:51 UTC of August 27th 2016, with a total of
112 13 scans (one scan was incomplete due to partial data loss). The spatial resolution of these
113 images varies from ~ 90 down to ~ 20 km. The southern aurora was observed from 15:06 to
114 19:51 UTC of August 27th 2016, with a total of 10 scans acquired. The spatial resolution of these
115 images varies from ~ 50 km to ~ 130

116 **3 Data processing**

117 In some particular cases, the JIRAM *L* band images evidence significant contamination arising
118 from strong signals present in the companion *M* band detector. The origin of the problem is not
119 known at present but remains under study. Possible explanations include stray light within the
120 optical system, and/or electron leakage on the detector. The same effect was evidently already
121 present in JIRAM calibration observations of Earth's moon acquired during Juno's Earth flyby in
122 2013 (Adriani et al., 2016). However, the contamination was very faint and it remained
123 unnoticed until data from Jupiter became available. In fact, this effect is relevant only for the
124 *L*band detector, and it is observed only when the *M* band detector (which is beneath the *L* band
125 one) receives a strong signal from Jupiter in its field of view (figure 1). The most unfavorable
126 configuration occurs when looking JIRAM images the northern pole: in this case Jupiter fills the
127 *M* band imager field of view. The intensity of the interference is higher than the radiance from
128 H_3^+ emission, and it is therefore necessary to correct the data.

129 By analyzing the intensity and spatial variation of the interference observed when no real signal
130 is present in the *L* band image FOV, it appears that the contamination is less intense for pixels
131 that are distant from the *M/L* band border. The spatial variation of the interference signal has
132 been fit with an exponential function with three free parameters:

133
$$N = C e^{-x/\lambda} + D \quad (1)$$

134 where N is the noise count rate, C is an intensity value, λ is a scale length, D is a constant
 135 background value, and x is the distance, in pixels, from the L/M band border along the detector
 136 column. For each acquisition, and for each column of the image matrix, parameters C and D are
 137 variable. In contrast, the scale length is found to be almost constant in time and uniform along
 138 columns, with a value of about 20; but it too can be slightly tuned to improve the performance of
 139 the noise-removal algorithm. In principle, C is likely related to the intensity of the signal that is
 140 present in the M band channel. However, during scientific operations at Jupiter, JIRAM never
 141 takes both M and L images at the same time. Hence, a different approach is taken to find C and
 142 remove the constant background signal. We subtract the count rates of pixels in a subsequent
 143 image viewing the same surface location, and we assume that the signal has not changed
 144 between acquisitions 30 seconds apart, whereby D is canceled, and C can be obtained from:

145
$$N_1 - N_2 = C(e^{-x_1/\lambda} - e^{-x_2/\lambda}) \quad (2)$$

146 This also assumes, as a necessary approximation, that C is constant in the same column on two
 147 subsequent images.

148 At the end of the procedure the background D is still not evaluated, but it is usually less than ~ 5
 149 $10^{-5} \text{ W m}^{-2} \text{ sr}^{-1}$ and does not significantly affect the data, since the instrument noise equivalent
 150 radiance (NER) is $10^{-5} \text{ W m}^{-2} \text{ sr}^{-1}$. In addition, before every science image acquisition, JIRAM
 151 performs a “background frame” acquisition in the anti-nadir direction (dark sky image), and
 152 subtracts that from the targeted science image. This also allows removal of the focal plane’s
 153 dark current generated by the spurious accumulation of thermal electrons, and the thermal
 154 emission generated by the instrument’s inner walls and components.

155 In this way, it is possible to determine the parameters characterizing the noise contribution and
 156 partially remove the interference from the L band images (primarily northern aurora). The
 157 residual noise, and some artifacts arising from the noise removal procedure, are still visible in
 158 figure 4, but they do not affect the scientific interpretation of the data. We expect that turning
 159 off the JPEG compression currently employed to minimize telemetry resource usage will help in
 160 removing contamination from the data, because some artifacts are introduced by the JPEG
 161 compression as well, and not included in the corrections implemented with equation 2.

162 The measured radiance is mapped onto a reference surface 500 km above the 1 bar level using
 163 SPICE/NAIF routines and ancillary data (Acton, 1996). We chose this level as an average
 164 altitude, assuming most of the auroral emission originates in the vicinity (Grodent et al., 2001,
 165 Hiraki et al., 2008). The accuracy of the mapping to 500 km altitude is about as good as the
 166 projected pixel size (from 20 to 130 km, see above).

167 Juno’s vantage point is close to the planet, and rapidly evolving along the spacecraft trajectory,
 168 so the emission angle also evolves rapidly. A higher emission angle implies a longer column for
 169 the emitted radiation. The image intensity is adjusted (multiplied by the cosine of the emission
 170 angle), assuming that radiance is constant along such column, to normalize the measured
 171 radiance to that coming from a vertical column. This also implies that there is no methane
 172 absorption above the H3+ emission region; in fact, the spectrometer measurements of the
 173 auroral region (made with the same viewing geometry of the imager) show that even where the
 174 methane emission is large, it is always superimposed to the H3+ spectrum, this indicates that

175 the two molecules either co-exist at the same altitudes or the methane layer is below the H₃⁺
176 layer (Dinelli et al., 2017; Adriani et al., 2017; Moriconi et al., 2017). The image intensity is not
177 the total H₃⁺ emission, but only the segment in the filter passband.

178 **4 Satellite footprints**

179 Figures 2 and 3 show a total of 8 mosaic images of south aurora. White dashed lines show (from
180 outside to inside): the magnetic mapping of the orbits of Io, Europa, Ganymede, and 30 Jupiter
181 Radii (as a reference for the main oval) calculated using the VIP4 model (Connerney et al., 1998)
182 combined with a model magnetodisc (Connerney et al., 1981). The white dots indicate the
183 footprints of the positions of the moons (main spots, also indicated by letters I, E, G) during the
184 observations.

185 The footprints (FP) of Io and Europa are very evident in the 270°-0° SIII longitude sector, and
186 the agreement with the VIP4 model footprint locations is so good that we plot the VIP4
187 reference ovals only outside of the JIRAM image to avoid obscuration of the satellite related
188 features. Unfortunately, for these images, the instantaneous satellite footprints lie outside of the
189 mapped part of the aurora, and only the trailing tail is visible. In the case of Io, the distance
190 between the calculated footprint location and the closest part of the visible tail is ~30° in
191 longitude (~one hour of Jupiter-Io relative rotation). The tail extends for at least 90° in
192 longitude with decreasing intensity but without appreciable change in its thickness (~500 km).
193 The poleward edge is less sharp than the other one, as there is no auroral emission
194 equatorward of the footprint of Io (i.e. no significant particle precipitation originating inside of
195 Io's orbit). The brightness of Io's footprint decreases almost exponentially with a scale of ~2
196 hours (~70 degrees), and it appears that the Io's footprint tail is even longer if observed on
197 unprocessed images (figure 1, panel *B*). Similar inferences apply to Europa's footprint; it has a
198 similar intensity as Io's, but it is shorter and, being closer to the main oval, it is observable only
199 for few tens of degrees in longitude. The footprint of Ganymede is visible, and it has two main
200 spots (Bonfond et al., 2013a, 2013b, 2017) ~10 degrees above the predicted locations. It is
201 visible particularly in figure 3; the two spots are visible in panels *A* and *D*; in panel *C* they form a
202 segment and they are undistinguishable. In figure 2, it occurs to be too close to a stable, intense
203 emission feature of the main oval, which covers the footprint. A very faint tail may be present.

204 Figure 4 shows four mosaic images of north aurora after data processing. The green dashed line
205 is the statistical oval (UV) for that month as in Bagenal et al. (2014). The green spots are the
206 expected locations of the Ganymede, Europa and Io footprints according to the statistical
207 analysis of Hess et al. (2011). None of the main footprint spots are visible in the data; Io and
208 Europa are very far from the FoV, and Ganymede is confused with the main oval emission. For
209 this reason, no footprint model is added to the figure. Only a very tenuous part of the tail of Io
210 may be visible close to 0°E, 80°N, but this feature is attributed to Io only because the positions
211 given by Hess et al., (2011) are in correspondence with that feature.

212 **5 Main oval**

213 Earlier UV observations (Gerard et al., 1994; Ballester et al., 1996, Grodent et al., 2003) show
214 that the shape of the statistical UV main auroral oval is quite repeatable in a Jupiter fixed frame,
215 although second-order variations occur on time scales of tens of minutes, which is comparable
216 to the time resolution of the mosaics (for this reason we prefer not to integrate all data into a

217 single image). Variations include intensifications (~50% increase) of main, stable emission
218 features, and creations, movement and disappearance of minor structures.

219 Both in the UV and IR spectral ranges, the Jovian auroral morphology, on a global scale, is very
220 similar and commonly divided into three main components: 1) outer emissions (including the
221 footprints), 2) main oval (or main emission) and 3) polar emissions (e.g. Satoh and Connerney,
222 1999a,b, Clarke et al. 2004, Radioti et al., 2013, Grodent 2015). UV auroral features mainly
223 result from inelastic collisions of energetic electrons of magnetospheric origin with atmospheric
224 molecular hydrogen, whereas IR auroral emissions are due primarily to thermal emissions from
225 the H₃⁺ molecular ion at altitudes above the Jovian homopause.

226 As in UV images (Grodent et al., 2003, Gladstone et al., 2017, Connerney et al., 2017), the main
227 oval (both south and north ones) shows a narrow single arc in about one half of the oval, and
228 multiple arcs plus broad diffuse emissions in the other half. In the infrared, it seems that, in the
229 south, the broad region is between 270° and 0°, and a single arc is visible between 90° and 180°
230 (however, 180°-270° is not covered in the south pole). However, as Juno's UV and IR images
231 were not obtained at the same instant in time, during this perijove pass, we urge caution in
232 direct comparison of the two. In the north, a main single arc (plus some parallel secondary arcs)
233 is visible between 150° and 270° (magnetic longitudes), and the broad, multi-arc region covers
234 the remaining part. In both hemispheres, the diffuse region shows multiple structures of
235 coherent pattern. The northern aurora, for example, shows concentric arcs of similar
236 morphology (~200 km thick) placed from the main oval poleward, so that one might infer that
237 such a region is still magnetically conjugate with the southern aurora, i.e., closing across the
238 magnetic equator. These structures may correspond to a filamentation of alternatively upward
239 and downward current, in contrast to the simple paradigm of a single current loop connecting
240 the magnetosphere and the ionosphere. Part of the remaining region might map to the outer
241 magnetosphere, possibly related to a sector of the Dungey and Vasyliunas cycle flows (Cowley et
242 al., 2003; Grodent et al., 2003).

243 The unprecedented spatial resolution of the JIRAM IR observations helps constrain the
244 thickness of the single arc region, which is found to be uniformly equal to 500 km for the south
245 and 700 km for the north. This could help constraining the theoretical models such as that of
246 Cowley and Bunce (2001), as discussed in Grodent et al. (2003).

247 The southern aurora appears significantly brighter at the time of observation (~50% higher
248 intensity), as found in the spectrometer measurements (Adriani et al., 2017; Dinelli et al., 2017).
249 Three or four diffuse emission spots, placed at 0° System III west longitude and outside the
250 main oval in the south, are visible in the spectrometer data as well, and can be linked with
251 similar features in the north aurora at 0° longitude.

252 The local time variation of the emission is not easy to quantify at present. Because of the
253 configuration of JIRAM FoV and Juno orbit, observation of the dawn sector is correlated with
254 low emission angle. Even if the data are corrected for the emission angle variations (see section
255 3), an unavoidable observation bias could remain. If we compare the emission for a given
256 feature at different local times, there are some indications that the emission decreases after
257 dawn and the increases again at noon local time, in agreement with observations reported by
258 Adriani et al. (2017). A specific detailed analysis is needed to confirm this.

259 **6 Summary, conclusions and future perspectives**

260 JIRAM collected ~ 6 Gb of data before and after PJ1, and the investigation was extremely
261 successful in addressing its primary scientific objectives. In particular, the north and south
262 aurorae have been mapped by both the spectrometer and the *L* band imager channel. High-
263 resolution images of both poles show very thin structures (few hundreds of km) that have the
264 tendency to remain compact within time scales of the order of 1 hour. Although the footprints of
265 Europa and Io fell outside the JIRAM FoV in the images acquired in this first periapsis pass, their
266 tails were clearly detected, with a structure both well defined (few hundreds of km width) and
267 extended along the satellite L-shell (at least 180 degrees longitude, probably more). The
268 footprint of Ganymede, and possibly its tail, is visible in the southern aurora.

269 Inside the main oval, two different types of structures are observed: multi-arc structures, and
270 bright or dark spots. The multi-arc structures appear both in the northern and southern pole
271 close to the 0° meridian (in the north, such arcs are very thin) and we interpret these
272 structures, similar in shape as the main oval, as magnetically conjugate features, connecting
273 across the magnetic equator. In particular, the north aurora filaments may be interpreted as
274 alternatively upward and downward current.

275 In the north, inside main oval, small, bright, transient spots are observed with persistence
276 lifetime of hours or less. Outside of the main oval, bright spots are clearly seen close to 0°
277 longitude. There may be signatures of plasma injections, and they are substantially stable in a
278 SIII reference.

279 In the south, a very evident circular region, almost at the geographical pole, shows a strong
280 depletion of H₃⁺ emissions. This feature it is partially surrounded by a very bright arc,
281 characterized by significant intensity variations.

282 JIRAM did not collect data on PJ 2 and PJ 3, as a result of the interruption of normal spacecraft
283 operations, but during PJ4 JIRAM returned to normal science operations, to continue
284 spectrometry and imagery of the aurorae.

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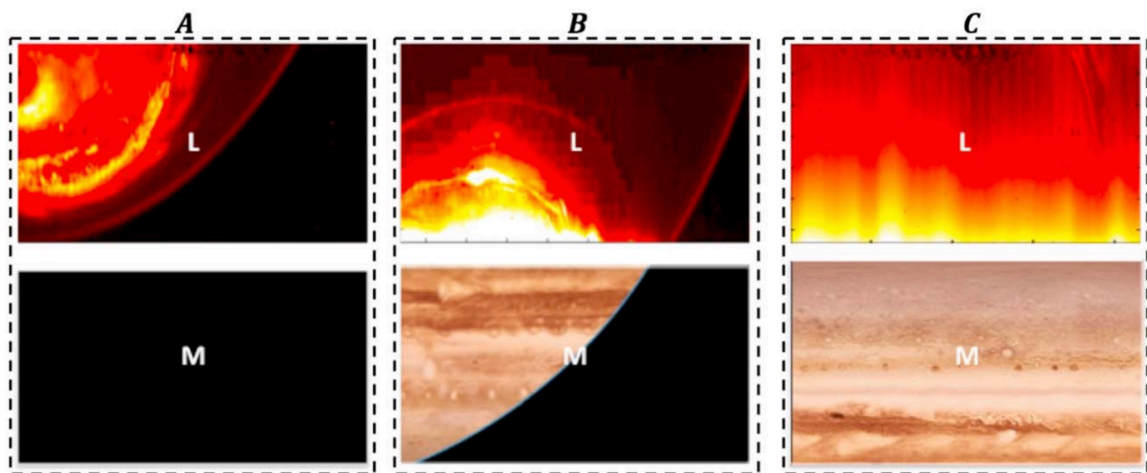
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Figure 1. Examples of L band data and contamination (top panels) function of M channel pointing (bottom, graphic art). A: South Aurora, very low contamination, M band FoV is pointing towards empty space. B: South Aurora, medium contamination in the bottom of the image; M band FoV is partially filled by Jupiter. C: North Aurora, very high contamination, M band FoV is completely filled by Jupiter.

356

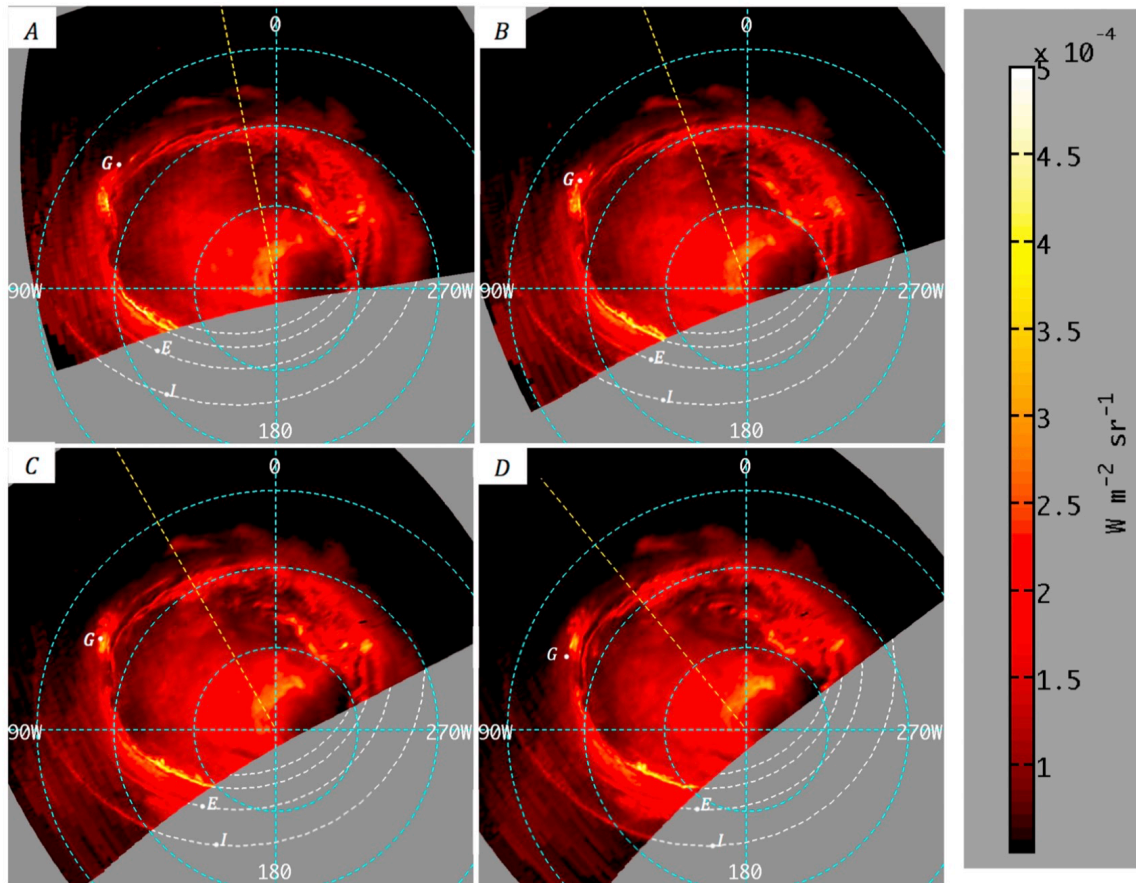


Figure 2 Mosaic maps of emission ($3.3\text{-}3.6 \mu\text{m}$ average radiance) from south aurora taken on August, 27th 2016. Cyan dashed circles are parallels at 80° , 70° and 60° latitude; longitudes are SIII; Sun direction is indicated by yellow line. White dashed lines are footprints of moons and 30 RJ according to VIP4 model (see text for explanations). Starting UTC times of observations are: 17:53:59 (panel A); 18:09:21 (B); 18:24:43 (C); 18:40:36 (D). White points are predicted footprint positions indicated by letters I, E and G.

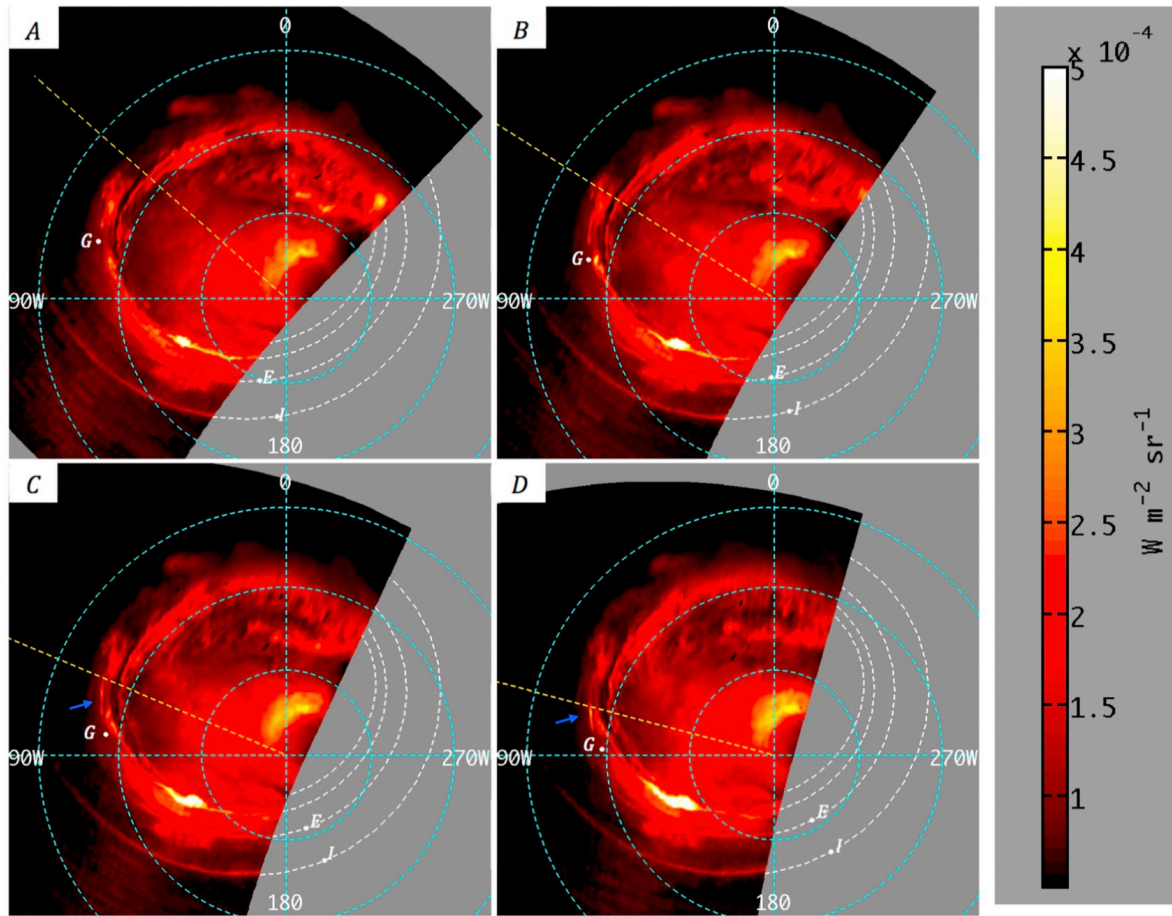


Figure 3 Same as figure 2, starting UTC times of observations are: 18:55:58 (panel A); 19:11:20 (B); 19:26:42 (C); 19:41:34 (D). A blue arrow (panel D only) indicates the feature that is identified as Ganymede footprint.

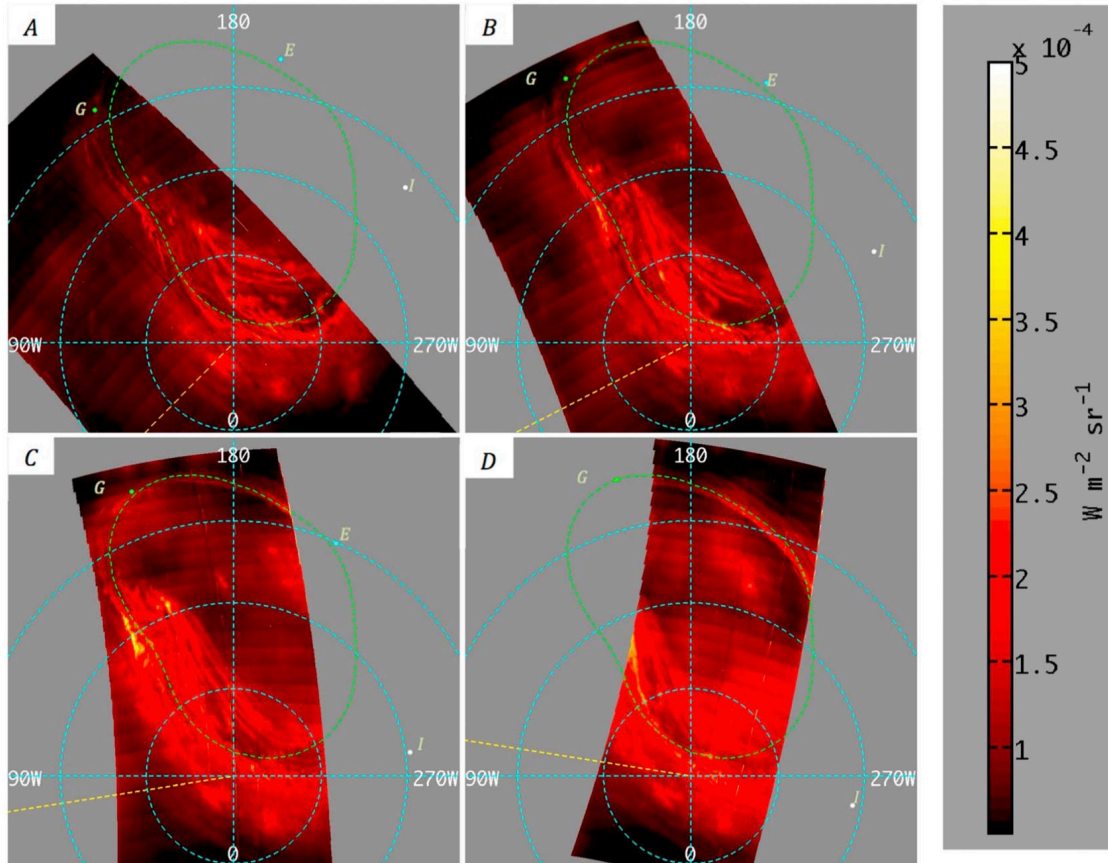


Figure 4. Same as figure 2, for north aurora. Green dashed line: statistical oval for that month as in Bagenal et al. (2014). Green spots are (clockwise) statistical positions of Ganymede, Europa and Io footprints (Hess et al., 2011; Europa FP position at the time of panel D was not available). Starting times of observations are: 08:53:58 (panel A), 09:24:11 (B), 09:54:23 (C), 10:24:05 (D).