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Concurrent ultraviolet and infrared observations of the north Jovian aurora during Juno's first perijove

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ABSTRACT

The UltraViolet Spectrograph (UVS) and the Jupiter InfraRed Auroral Mapper (JIRAM) observed the north polar aurora before the first perijove of the Juno orbit (PJ1) on 27 August 2016. The UVS bandpass corresponds to the H_2 Lyman and Werner bands that are directly excited by collisions of auroral electrons with molecular hydrogen. The spectral window of the JIRAM L-band imager includes some of the brightest H_3^+ thermal features between 3.3 and 3.6 µm. A series of spatial scans obtained with JIRAM every 30 s is used to build up five quasi-global images, each covering ∼12 min. of observations. JIRAM's best spatial resolution was on the order of 50 km/pixel during this time frame, while UVS has a resolution of about 750 km. Most of the observed large-scale auroral features are similar in the two spectral regions, but important differences are also observed in their morphology and relative intensity. Only a part of the UV-IR differences stems from the higher spatial resolution of JIRAM, as some of them are still present following smoothing of the JIRAM images at the UVS resolution. For example, the JIRAM images show persistent narrow arc structures in the 100°–180° S_{III} longitude sector at dusk not resolved in the ultraviolet, but consistent with the structure of in situ electron precipitation measured two hours later. The comparison between the H_2 intensity and the H_3^+ radiance measured along two radial cuts from the center of the main emission illustrates the complex relation between the electron energy input, their characteristic energy and the H_3^+ emission. Low values of the H_3^+ intensity relative to the H_2 brightness are observed in regions of high FUV color ratio corresponding to harder electron precipitation. The rapid loss of H_3^+ ions reacting with methane near and below the homopause appears to play a significant role in the control of the relative brightness of the two emissions. Cooling of the auroral thermosphere by H_3^+ radiation is spatially variable relative to the direct particle heating resulting from the precipitated electron flux.

1. Introduction

Jupiter's far ultraviolet (FUV) aurora was first detected from spectra obtained with the far ultraviolet spectrometers (UVS) on board the Voyager 1 and 2 spacecraft as they flew by the planet in 1980. They measured HI Lyman-α and H_2 Lyman and Werner bands emissions from both polar regions (Sandel et al. 1979). UVS latitudinal scans suggested that the UV auroral oval was located near the magnetic footprint of the Io orbit, although differences were pointed out in some longitude sectors (Connerney, 1992). By contrast, the first direct FUV images of the northern aurora obtained with the Hubble Space Telescope (HST) (Dols et al., 1992; Gérard et al., 1993) indicated that the main auroral emission mapped along Jovian magnetic field lines originating from the plasma sheet at an equatorial distance between 15 and 30 Jovian radii (R_J). This was confirmed by the detection of the Io magnetic footprint on Jupiter in the infrared (Connerney et al., 1993) mapping to 5.9 R_J and distinctly separated by about 8° from the main auroral emission. Considerable improvements of the sensitivity and performances of the successive ultraviolet cameras on board HST demonstrated the complexity and time variability of the

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different features of the auroral morphology. Their characteristics have been reviewed by several authors (Bhardwaj and Gladstone, 2000; Clarke et al., 2004; Badman et al., 2014; Grodent, 2015). Several distinct emission regions are identified: main, polar and equatorward emission and satellite footprints.

Jupiter's main auroral emission in the UV forms a relative stable strip of emission around the magnetic pole with variability on time scales of minutes to hours (Gérard et al., 1994; Grodent et al., 2003a). It is estimated to contribute 50% of the Jovian auroral brightness integrated over high latitudes (Nichols et al., 2009). HST observations of the north dayside aurora have shown that there is a persistent asymmetry between the dawnside main emission, which is generally narrow and continuous, and the duskside main emission, which is usually broader and sometimes appears to separate into several arcs. Unlike the H_2 Lyman and Werner bands, the infrared H_3^+ bands are thermal emissions produced indirectly by the electron precipitation:

$$e + H_2 \rightarrow {H_2}^+ + 2e$$

followed by charge transfer:

$$H_2^+ + H_2 \rightarrow H_3^+ + H$$

The infrared (IR) emissions from the H_3^+ ion were first spectrally detected from the ground by Drossart et al., (1989) while Trafton et al., (1989) measured the H_2 quadrupole emission near 2 µm. The H_3^+ aurora was later imaged near 3.4 µm (Baron et al., 1991; Kim et al., 1992; Connerney and Satoh, 2000). The radiance of these bands depends linearly on the H_3^+ column density, but it also varies exponentially with the local temperature (Drossart et al., 1993). The H_3^+ emissions were mapped based on images from the NASA IRTF telescope by Satoh et al., (1996) who compared the global morphological characteristics of the IR emission to the UV images previously obtained with HST and found similar characteristics. Satoh and Connerney (1999) mapped the H_3^+ auroral emission over a complete rotation of Jupiter using a narrow filter at 3.43 µm and found a main peak brightness near 75° N latitude, at a S_{III} longitude $\lambda_{III} = 260°$, and a secondary peak near 65° N, $\lambda_{III} = 165°$ They used the H_3^+ distribution to map back the corresponding magnetospheric sources. Raynaud et al., (2004) described spectral imaging observations and structures in the H_3^+ intensity distribution.

The aurora located poleward of the main emission ('polar emission') exhibits strong temporal variations. The north aurora has been divided into three regions named active, swirl and dark regions (Grodent et al., 2003b) on the basis of their statistical morphology and variability. The dark polar region is defined as the zone on the dawn side located poleward of the main emission. It is of very low intensity in the UV. The swirl region is in the center and shows intermittent bursts of emission. Finally, the active region on the dusk side is the area where time dependent bright flashes and other structures have been observed (Waite et al., 2001), with isolated transient features sometimes showing quasi-periodic variations (Bonfond et al., 2016). Polar emissions have also been observed at infrared wavelengths, and it has been shown that ~45% of the IR power emitted from the entire auroral region originates from the polar zone (Satoh and Connerney, 1999). Stallard et al., (2003) measured the H_3^+ ionospheric flow and brightness. In the north, they identified a dark polar region (DPR) where the plasma is stagnant and coupled to magnetotail magnetic field lines (f-DPR). They distinguished two additional regions: r-DPR corresponding to the UV dark region where the ion flow returns to co-rotation corresponding to the swirl region, and a bright polar zone (BPR) likely associated with the active region.

Equatorward of the main emission but poleward of the Io footprint and tail, diffuse emissions are observed in both the UV and the IR. The ultraviolet equatorward diffuse emissions extend from the main emission toward lower latitudes, occasionally forming a belt of emissions parallel to the main emission and/or patchy irregular emissions (Grodent et al., 2003b). Part of the equatorward UV diffuse emission appears associated with electron scattering into the loss cone by whistler mode waves near the pitch angle distribution boundary, leading to electron precipitation in the ionosphere (Radioti et al., 2009). UV and IR transient patches have been observed in the region between the Io footprint and the main emission (Dumont et al., 2015). They are the optical counterparts of magnetospheric injections (Mauk et al., 2002). The corresponding IR emissions contribute 20% of the total IR power emitted from the entire region according to Satoh and Connerney (1999).

Finally, electromagnetic interactions between Jupiter and its moons result in auroral signatures observed both in the H_2 ultraviolet and H_3^+ infrared emissions in Jupiter's upper atmosphere (see Bagenal et al., 2017 and references therein).

In the view prevailing so far, the energy powering the magnetospheric plasma finds its origin in the fast planetary rotation and its subsequent transfer into kinetic energy of magnetospheric electrons. Unlike the Earth's and Saturn's cases, conceptual models (Hill, 2001; Cowley and Bunce, 2001; Cowley et al., 2003) suggested that the relatively stable main auroral emission at Jupiter corresponds to the upward branch of a global current system flowing along magnetic field lines. Other acceleration processes appear to be at play in other regions of the magnetosphere. For example, pitch angle scattering of energetic electrons is thought to be the source of the diffuse aurora equatorward of the main oval (Coroniti et al., 1980; Bhattacharya et al., 2001; Radioti et al., 2009). Polar regions inside the main emission show rapidly varying and flaring structures whose origin is still largely unknown (Waite et al., 2001; Grodent et al., 2003b; Bonfond et al., 2016). Finally, the magnetic footprints of the Galilean satellites on the Jovian atmosphere appear to be generated by acceleration of electrons by a parallel electric field associated with the propagation of Alfvèn waves (Hess et al., 2010).

Before the Juno era, maps of the characteristic energy of the precipitated auroral electrons could only be obtained through ultraviolet spectral remote sensing. This method is based on the shape of the CH_4 absorption cross sections, which partly absorbs the H_2 emissions at wavelengths shorter than 140 nm but leaves the longer wavelengths unattenuated. Spectral images were analyzed to determine spatially averaged color ratio CR = I(155–162 nm)/I(123–130 nm), where the numerator is the photon flux integrated from 155 to 162 nm and the denominator is the total flux between 123 and 130 nm. The value of the H_2 FUV color ratio in the absence of any absorption is equal to ~1.1. Gérard et al. (2014) and Gustin et al. (2016) obtained maps of characteristic electron energies in the range 30–200 keV, with values as high as 400 keV in a bright morning event. The major source of uncertainties in the energy determination is linked to the uncertain vertical distribution of the absorbing hydrocarbons in the high latitude upper atmosphere.

Since the first Juno pass near its perijove (PJ1), unprecedented global views of the aurora have been obtained both in the ultraviolet with the UVS spectral imager and in the infrared with the JIRAM-L infrared camera. Early results collected in both polar regions during the PJ1 phase of the orbit have been recently summarized by Connerney et al. (2017). Early results from UVS during the Jupiter approach (Gladstone et al., 2017a) showed that only one of the four observed auroral brightenings was associated with a significant increase in solar wind ram pressure. Bonfond et al. (2017a) described the FUV morphology observed during the first perijove pass. They reported the presence of localized features showing indications of differential drift with energy, signatures of plasma injections in the middle magnetosphere and the presence of a well defined structure