Six pieces of evidence against the corotation enforcement theory to explain the main aurora at Jupiter

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Key Points:

• The corotation enforcement current system currently is the mainstream explanation for the main auroral emissions at Jupiter
• We expose six observational pieces of evidence that this theory is not the main explanation for these auroral emissions
• Improved theories should account for the local time variations in the magnetosphere and the importance of the plasma waves for the creation of auroral emissions.

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Abstract
The most remarkable feature of the ultraviolet auroras at Jupiter is the ever present and almost continuous curtain of bright emissions centered on each magnetic pole and called the main emissions. According to the classical theory, it results from an electric current loop transferring momentum from the Jovian ionosphere to the magnetospheric plasma. However, predictions based on these mainstream models have been recently challenged by observations from Juno and the Hubble Space Telescope. Here we review the main contradictory observations, expose their implications for the theory and discuss promising paths forward.

Plain Language Summary
The powerful auroras at Jupiter are very different from those at Earth and the mechanisms generating them differ as well. Their most obvious features is a relatively continuous auroral curtain surrounding the magnetic poles. The classical explanation for its presence involves an electric current system that allows particles in the magnetosphere to rotate with planet. While these models explain some characteristics of the auroras, recent observations from the NASA Juno spacecraft and the Hubble Space Telescope challenge this theoretical framework.

1 Introduction
The ultraviolet (UV) auroras at Jupiter can be separated into three almost equally powerful components (Nichols, Clarke, Grard, Grodent, & Hansen, 2009; Grodent et al., 2018): 1) the main emissions (ME), which are forming an almost continuous curtain of auroral emissions around the magnetic pole, 2) the polar emissions located poleward of the ME and 3) the equatorward, or outer, emissions, essentially comprised between the ME and Io’s footpath (Figure 1a). The auroral footprints of the Galilean moons, are often cited as a fourth component, even if their total emitted power is much smaller (∼30 GW for the Io footprint (Bonfond et al., 2013), compared to ∼500 GW for the ME (Grodent et al., 2018)). The ME magnetically maps to distances typically ranging from 20 to 60 Jovian radii ($R_J$) (Vogt et al., 2011), though in rare instances, this distance dropped to near to the orbit of Ganymede (15$R_J$) (Bonfond et al., 2012). Since it became clear that the main emissions did correspond neither to the open-closed field line boundary (or the outer-most magnetosphere) nor to the Io torus (Dols et al., 1992), the most widely accepted explanation for this auroral feature involves a large scale current system coupling the magnetospheric plasma to the ionosphere (Hill, 1979, 2001; Cowley & Bunce, 2001; Southwood & Kivelson, 2001).

According to this theoretical frame, the current system transfers momentum from the ionosphere to the plasma sheet. It flows radially outward in the plasma sheet and the $J \times B$ force accelerates the magnetospheric plasma towards corotation with the planet. At the other end of the circuit, equatorward Pedersen currents slow down the charged particles in the ionosphere, which interact with the rest of the upper atmosphere via ion-neutral collisions. Field aligned currents flow between these two sections of the loop, upward from the ionosphere to the magnetosphere in the middle magnetosphere and in the opposite direction in the outer magnetosphere (Figure 1b). In the plasma sheet, this current system starts at Io’s orbit, where fresh plasma is injected in the magnetosphere from the volcanic moon’s neighbourhood. This plasma then progressively migrates outward to be eventually released in the Jovian magnetotail. As the radial distance increases and in the absence of additional forces, the conservation of the angular momentum dictates that the angular velocity of the plasma would decrease. Thus, to maintain corotation, the required momentum transfer from the ionosphere to the magnetosphere increases, as do the currents. Models predict the field aligned currents peak at a distance close to the region where the system becomes unable to maintain full corotation with the planet.
also known as the corotation breakdown distance. In the region where the upward currents peak, field aligned potential are expected to form and accelerate electrons into the atmosphere, causing the main auroral emissions.

Many observations gathered either by the spacecraft that have visited the Jovian system through the years or by Earth based telescopes appear to support some elemental processes in this framework. First, the magnetospheric plasma at Jupiter is either in full corotation with the planet, or, at least, significantly rotating with it, indicative that momentum is indeed transferred from the ionosphere/thermosphere to the magnetosphere. It should however be noted that this is also true for Saturn, and yet, the associated current system does not give rise to significant auroras (the auroras at Saturn are mainly caused by other processes). Then, sub-corotation and velocity shears in the polar ionosphere of Jupiter have been observed, indicative of a torque being exerted on the inner polar regions of the ionosphere (i.e. Johnson et al., 2017). It is also noteworthy that these models predict a location of the auroral emissions and a typical brightness consistent with the observations. The idea that corotation enforcement currents drive the ME also provides an explanation for the usually dimmer main emissions on their pre-dawn section, named the discontinuity (Radioti et al., 2008). As the shape of the dayside magnetopause forces the plasma in the dawn-side magnetosphere, its azimuthal velocity increases and the need for momentum transfer decreases. The field aligned currents inferred from Galileo magnetic field measurements in the equatorial plane are also minimum in this sector (Khurana, 2001). Furthermore, the equatorward expansion of the main emissions during time interval during which the mass outflow rate is expected to have increased is also consistent with the theory (Bonfond et al., 2012). Finally, the observation of the relationship between the precipitating energy flux in the main emissions and the mean electron energy were found to be consistent with the Knight-like relationship expected for quasi-static electric fields (Gustin et al., 2004; Grard et al., 2016), even if Clark et al. (2018) showed that Alfvénic acceleration could lead to the same kind of relationship.

However, while this model is widely accepted to be the explanation for the main auroral emissions and despite its successes, several observations contradicting the predictions of this theoretical framework concerning the main auroral emissions have recently started to accumulate. Some of these observations were actually known for a long time, while others were recently revealed by the NASA Juno mission.

2 Six pieces of evidence against the "corotation enforcement" explanation for the main emissions

2.1 Global auroral brightening with solar wind compression

One of the first prediction of the corotation enforcement currents models concerned the response to solar wind compressions and expansions. All these models predict that the ME aurora would dim as a response to a solar wind compression (Southwood & Kivelson, 2001; Cowley & Bunce, 2003). The first versions only considered steady state systems. A later iteration took the time variations into considerations (Cowley et al., 2007).

Observations of the infrared $H_3^+$ aurora before the Ulysses Jupiter fly-by showed an increase of the total emitted power with the increase of the solar wind (Baron et al., 1996). It was however not clear at the time that this increase was due to the main emissions, or whether it was related to a brightening of other regions. Studies based on Hisaki observations of the total auroral power in the ultraviolet reached the same conclusion (Kita et al., 2016). In other wavelengths (e.g. Gurnett et al. (2002) for the radio hectometric emissions, Dunn et al. (2016) for the X-rays owing to ion precipitation and Sinclair et al. (2019) for the infrared hydrocarbon emissions), increase of the auroral activity have also been found to correlate with compressed solar wind conditions. It should
be noted that these indices possibly involve processes taking place poleward of the ME, which may or may not be correlated with the ME. Analysis of the response of the UV aurora to a solar wind compression prior to the Cassini Jupiter fly-by showed that the main emissions brightened during a solar wind compression (Nichols et al., 2007). However, the exact timing of the response remained unclear, as the model of Cowley et al. (2007) predicted a possible brief ME enhancement right after the arrival of a compressed solar wind, before a prolonged dimming of the auroral emissions. Later HST observations of the aurora during either the New Horizons fly-by (Nichols, Clarke, Grard, & Groot, 2009; Clarke et al., 2009) or the arrival of Juno Nichols et al. (2017) suggested that some auroral brightenings are consistent with intervals of solar wind compressions. A recent study including observations from both Hisaki and the UV spectrograph on board Juno also described brightenings correlated with the solar wind compressions, but concluded that the exact timing of the brightening lagged the arrival of large solar wind shocks (Kita et al., 2019). They also found that the amplitude of the brightening did not scale with the disturbance of the dynamic pressure. In summary, these studies either conclude that the ME brightens with the arrival of a compression region, or conclude that the timing of the response is unclear, but none of them report the dimming expected from the theory.

Yao et al. (2020) observed the aurora with the Hubble Space Telescope as Juno was on the dawn flank of the magnetosphere. Juno encountered several time during intervals of compressed magnetosphere. Each time, the main emissions significantly brightened at all local times. Unlike all previous studies, this one does not rely on any propagation model of the solar wind, but directly assess the state of the magnetosphere. It is also remarkable that even the noon sector, which is where the compression effects should be the clearest, brightened compared to the quiet case. This study also confirms that hectometric radio emissions are systemically enhanced during solar wind compression. Finally, it should be noted that, while non-resolved enhancements of the auroras do not guarantee that the ME is the auroral component that caused it (see counterexample in Kimura et al., 2015, associated with internally driven reconfigurations), the enhancements of the ME seen by HST and Juno-UVS result in an enhancement of the total power compatible with those Hisaki and others observed simultaneously to solar wind shocks.

2.2 Brightness variations as a response to magnetic loading/unloading

Yao et al. (2019) directly compared the azimuthal and radial stretching of the dawn-side magnetic field as measured by Juno to the auroral output. During a time interval for which the magnetosphere was compressed, they noted that the auroras and the ME in particular were brighter than during quiet times. They also noted that the stretching of the magnetic field, or said in other words, the loading of energy in the magnetic field, oscillated during this interval. And, contrary to classical theoretical expectation, the aurora and the radio kilometric emissions increased during the unloading phases, as if the magnetic energy was converted into particle energy, similarly to what is observed on Earth.

2.3 Dawn/dusk brightness asymmetry

One of the most direct evidence of the radially outward flowing currents in the plasma sheet is the azimuthal bend back of the magnetic field. This angle is larger on the dawn flank of the magnetosphere than on the dusk flank. As a consequence, the main emissions are also expected to be brighter on dawn (Ray et al., 2014). However, a comparison of the dawn and dusk sides of the main emissions based on Hubble Space Telescope observations showed that the dusk side is typically 3 times brighter than the dawn side (Bonfond et al., 2015). A possible explanation is that, in addition to the corotation enforcement currents, another current system of the same magnitude and linked to the par-
tial ring current in the magnetotail also feeds into the auroral regions. It would consistently strengthen the total net field aligned currents on the dusk side and weaken the currents on the dawn side. Analysing the equatorial magnetic field measurements of the whole Galileo mission, Lorch et al. (2020) also concluded that azimuthal currents play a key role in determining the location of the field aligned currents. Furthermore, Vogt et al. (2019) noted that the dawn-dusk discrepancy on the bend back angle is even larger during solar wind compressions, which should lead to a brightening of the dawn arc of the ME but a dimming of the dusk arc if the corotation enforcement current were driving the main auroral emissions. Again, this is contrary to the observations, as the ME brighten at all local times during compressions of the magnetopause (Yao et al., 2020).

2.4 Dawn/dusk asymmetries in the particle velocity

In axisymmetric models, the velocity of the particles and the azimuthal component of the magnetic field (i.e. the bend back) are expected to be anti-correlated. However, comparisons of the dawn and dusk flanks of the Jovian magnetosphere show that the magnetic field bend back is larger in the dawn flank (Khurana & Schwarzl, 2005) as well as the velocity of the charged particles (Krupp et al., 2001). When considering the three dimensional shape of the magnetosphere, this actually make much sense. As the field lines are increasingly stretched in the magnetotail, the plasma’s angular velocity decreases. Then, on the dawn side, the field lines are still considerably stretched backward (compared to the dusk side), but the particles angular velocity increases as the particles are now moving radially inward. This illustrates again the limitations of axisymmetric models with regard to local time effects.

2.5 Field aligned currents are fragmented and asymmetric

The first Juno observations of the magnetic field above the Jovian auroras did not reveal the strong field aligned currents expected from the theory (Connerney et al., 2017), but a later analysis covering the first 11 Juno perijoves did reveal significant currents, with a combined mean value of 82 MA for the two hemispheres, which is in line with the estimates of the radial currents in the magnetosphere (Kotsiaros et al., 2019). However, they found that the current did not take the form of thin and regular current shells, but were fragmented and confined on longitudinal extent. Another unexpected feature was the strong asymmetry between the two hemispheres, with southern currents being approximately twice as large as in the north (58 MA compared to 24 MA). They attributed this difference to the magnetic field asymmetries leading to differences in the Pederssen conductivity between the two polar ionospheres.

2.6 Quasi-static potentials are not the main driver for the ME

One of the main finding of the Juno mission so far is the ubiquity of the stochastic acceleration processes for the charged particles in the polar regions. At Earth, the most steady and brightest auroral emissions are related to quasi-static potentials above the ionosphere which accelerate the charged particles (mostly electrons) into the upper atmosphere. Because the ME at Jupiter are even brighter and permanent, it was thought that such quasi-static potentials would also dominate the energization of the charged particles. Such quasi-static potentials have indeed seldom been discovered by Juno, but even in these specific locations, the precipitating energy flux remains dominated by stochastic processes and most electron distributions are bi-directional along the field lines (Mauk et al., 2018). This finding is a surprise since corotation enforcement models rely on the formation of such electric potentials through the Knight relationship (or a variation thereof) between the precipitating energy flux and the electron energy (e.g. Cowley & Bunce, 2001; Ray et al., 2010; Tao et al., 2016). Since bi-directional electron acceleration appear to be the norm, the UV auroral brightness, which is almost solely related to the precipi-
tating electron energy flux, is not a reliable proxy for the intensity of the net up-going field aligned currents. An even more unexpected and important finding is the discovery of bi-directional electron beams and proton inverted-V structures on the same field line (Mauk et al., 2018, 2020), meaning that a downward current is compatible with downward moving electrons producing UV aurora. This indicates that several processes can co-exist at different altitudes on the same field line. Thus the presence of UV aurora is not even an indication of up-going currents.

3 Conclusions

It is not expected for 1-D (quasi-)stationary models to explain all the details of the auroras at Jupiter, as they are simplifications built to better understand the most important processes at play. Nevertheless, specific predictions can be made out of these models and a number of them were challenged by the measurements. It is noteworthy that most of the observations mentioned here above concern the generation of the auroras, which are associated, but not strictly equivalent, to the magnetosphere-ionosphere coupling processes and their related currents. After all, the magnetospheric plasma at Jupiter is rotating and field aligned current have indeed been observed. Thus, it is not clear yet whether the question of the origin of the main emissions at Jupiter requires some adjustments of the mainstream theory or a complete paradigm shift. However, recent works have suggested possible paths forward. First, the idea that the auroral emissions are a direct image of the up-going field aligned currents is invalidated by Juno’s measurements (Mauk et al., 2018). If the particle acceleration process is stochastic, even regions of down-going currents would have a significant flux of down-going electrons creating auroral emissions. Then, it appears that the explanatory power of axisymmetric models is limited at Jupiter, as local time effects, fragmentation phenomena and non-axisymmetric current systems are critically important. Finally, the findings reported here above also suggest that wave processes and wave-particle interactions should be assessed more carefully rather than assuming steady state continuous currents. A closer examination of the energy transferred by Alfvén waves already showed some promising results, both theoretically (Saur et al., 2018) and observationally (Gershman et al., 2019). Finally, it could also be of critical importance for magneto-hydrodynamic simulations of the Jovian magnetosphere to focus on the Poynting flux and the contribution of Alfvén wave power rather than on the field aligned currents when comparing their outputs to auroral images in order to provide crucial insight in understanding the origin of the main emissions.

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Figure 1. Panel a) A typical polar projection of the southern UV aurora as seen by Juno-UVS on 21 December 2018. The red arrows highlight the main emissions, which are the brightest on the dusk flank (orange) and the dimmest in the pre-noon sector (dark red). The green arrows highlight the outer emissions. The polar emissions were weak on that particular day. Panel b) Classical scheme of the corotation enforcement currents model to explain the main auroral emissions at Jupiter (After Cowley & Bunce (2001)). The dashed cyan lines represent the magnetic field and the solid red lines represent the electric currents. The electric fields accelerating the electrons into the aurora are shown in green.
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