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Special Section:
Jupiter Midway Through the Juno Mission

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

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Six Pieces of Evidence Against the Corotation Enforcement Theory to Explain the Main Aurora at Jupiter

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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 widely accepted theory, it results from an electric current loop transferring momentum from the Jovian ionosphere to the magnetospheric plasma. However, predictions based on this theory 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 feature is a relatively continuous auroral curtain surrounding the magnetic poles. The classical explanation for its presence involves an electric current system that causes 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 (Grodent et al., 2018; Nichols et al., 2009): (1) the main emissions (MEs), which form an almost continuous curtain of auroral emissions around the magnetic pole; (2) the polar emissions located poleward of the MEs; and (3) the equatorward, or outer, emissions, essentially confined 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 MEs (Grodent et al., 2018). The MEs magnetically map to distances typically ranging from 20 to 60 Jovian radii (R_J) (Vogt et al., 2011), though in rare instances, the lower boundary dropped to near to the orbit of Ganymede ($15R_J$) (Bonfond et al., 2012). Since it became clear that the MEs corresponded neither to the open-closed field line boundary (or the outermost 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 (Cowley & Bunce, 2001; Hill, 1979, 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 toward corotation with the planet. At the other end of the circuit, equatorward-flowing 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 neighborhood. This plasma then progressively migrates outward to be eventually released in the Jovian magnetotail. As the radial distance increases, 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

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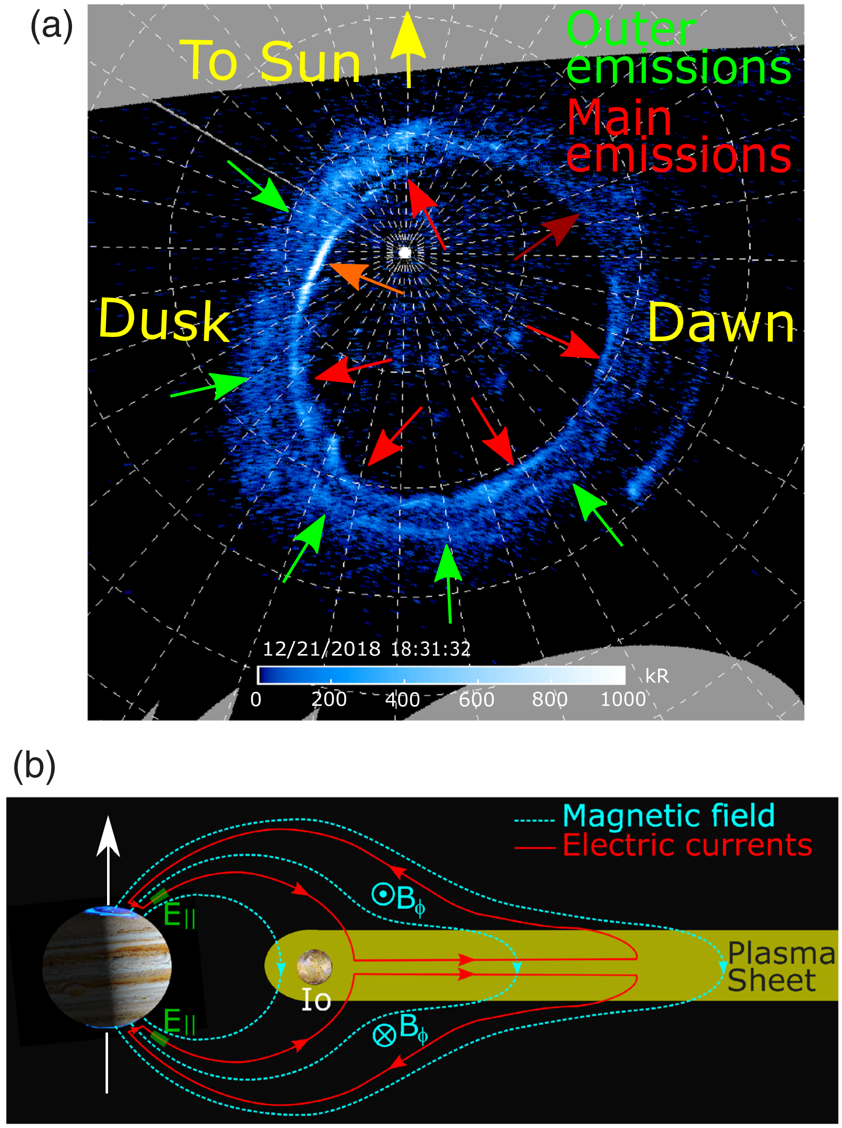

Figure 1. (a) A typical polar projection of the southern UV aurora as seen by Juno-UVS on 21 December 2018. The red arrows highlight the main emissions, which are the brightest on the dusk flank (orange) and the dimmest in the prenoon sector (dark red). The green arrows highlight the outer emissions. The polar emissions were weak on that particular day. (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.

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 and based on the Knight kinetic theory (Knight, 1973) or a modified version of it (Ray et al., 2009), field-aligned potentials are expected to form and accelerate electrons into the atmosphere, causing the main auroral emissions. It should be noted that while it is not a formal requirement of the corotation enforcement theory, most models (i.e., individual published studies based on this theoretical framework) are axisymmetric, or at least locally axisymmetric, meaning that they assume that net azimuthal fluxes can be neglected.

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 elementary 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, see review in Stallard et al., 2019). Then, subcorotation 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 (e.g., Johnson et al., 2017). It is also noteworthy that these models predict a range of magnetic latitudes of the auroral emissions and a typical brightness consistent with the observations. The idea that corotation enforcement currents drive the MEs also provides an explanation for the usually dimmer MEs on their prenoon section, named the discontinuity (Radioti et al., 2008; Ray et al., 2014). As the shape of the dayside magnetopause forces the plasma to flow radially inward in the dawnside 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 MEs during a time interval during which the mass outflow rate is believed to have increased is also qualitatively consistent with the theory (Bonfond et al., 2012). Finally, the observation of the relationship between the precipitating energy flux in the MEs and the mean electron energy were found to be consistent with the Knight-like relationship expected for quasi-static electric fields (Gérard et al., 2016; Gustin et al., 2004). It should however be noted that Clark et al. (2018) showed that Alfvénic acceleration could lead to the same kind of relationship.

However, while this theory is widely accepted as 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 started to accumulate. Some of these observations have been known for a long time, while others were recently revealed by the NASA Juno mission.

Subsections 2.1 and 2.2 discuss the limits of the local axisymmetry and north-south symmetry hypothesis generally adopted in the models of the current system giving rise to these auroral emissions. The next three subsections discuss observations challenging the link between radial currents and auroral intensity. And the final section discusses the relevance of quasi-static potentials to generate the MEs.

2. Six Pieces of Evidence Against the “Corotation Enforcement” Explanation for the MEs

2.1. Dawn/Dusk Asymmetries in the Particle Velocity

In models assuming independent longitudinal cuts through the magnetosphere (local axisymmetry), the velocity of the particles and the azimuthal component of the magnetic field (i.e., the bend-back) are expected to be anticorrelated. 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 makes much sense. As the field lines are increasingly stretched in the magnetotail, the plasma's angular velocity decreases. Then, on the dawnside, the field lines are still considerably stretched backward (compared to the duskside), but the particles angular velocity increases as the particles are now moving radially inward. Another way to understand that is to consider the conservation of the rate of flux transport across meridian planes as a function of local time. Assuming that meridian cuts at dawn and dusk have approximately the same surface, the lower normal magnetic field strength at dawn (Vogt et al., 2011) must be compensated with higher azimuthal velocities. However, this observation is contrary to the predictions from 1-D models based on torque balance, as previously noted by Ray et al. (2014).

2.2. 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 was fragmented and confined in longitudinal extent. While this fragmentation is generally overlooked in the theoretic models, it appear, at least qualitatively consistent with the strong plasma turbulence observed in the equatorial plane by Galileo (Mauk & Saur, 2007). Another striking 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 Pedersen conductivity between the two polar ionospheres. However, conjugate observations of the MEs by HST did not lead to a clear cut relationship between the surface magnetic field and the emitted power in the UV (Gérard et al., 2013). The large asymmetries of the Jovian magnetic field have been neglected in theoretical models, including magneto-hydrodynamic (MHD) simulations, so far, but they appear to have important consequences on both the current and the aurora.

2.3. Dawn/Dusk Brightness Asymmetry

The most direct pieces of 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 MEs are also expected to be brighter at dawn (Ray et al., 2014). However, a comparison of the dawnside and duskside of the MEs based on Hubble Space Telescope observations showed that the duskside is typically three times brighter than the dawnside (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 partial ring current in the magnetotail also feeds into the auroral regions. It would consistently strengthen the total net field-aligned currents on the duskside and weaken the currents on the dawnside. Analyzing 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 MEs 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 MEs brighten at all local times during compressions of the magnetopause (Yao et al., 2020).

2.4. Global Auroral Brightening With Solar Wind Compression

One of the predictions of the corotation enforcement currents models concerned the response to solar wind compressions and expansions. All these models predict that the MEs aurora would dim as a response to a solar wind compression, due to the smaller size of the magnetosphere, to the increased angular velocity of the plasma which is pushed inward and to the lower resulting currents (Cowley & Bunce, 2001, 2003; Southwood & Kivelson, 2001). The first versions of these models only considered steady-state systems. A later iteration took the time variations into consideration (Cowley et al., 2007).

Observations of the infrared H_3^+ aurora before the Ulysses Jupiter flyby showed an increase of the total emitted power with increase of solar wind ram pressure (Baron et al., 1996). It was, however, not clear at the time that this increase was due to an intensification of the MEs or whether it was related to a brightening of other regions. Studies based on Hisaki observations of the total auroral power in the UV reached the same conclusion (Kita et al., 2016). In other wavelengths (e.g., Gurnett et al., 2002; Zarka & Genova, 1983, 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 has 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 MEs, which may or may not be correlated with the MEs. Analysis of the response of the UV aurora to a solar wind compression prior to the Cassini Jupiter flyby showed that the MEs 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 MEs enhancement right after the arrival of a compressed solar wind, before a prolonged dimming of the auroral emissions. Subsequent HST observations of the aurora during both the New Horizons flyby (Clarke et al., 2009; Nichols et al., 2009) and 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 MEs brighten 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 the magnetopause several times during intervals of compressed magnetosphere. Each time, the MEs 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 assesses 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 nonresolved enhancements of the auroras do not guarantee that the MEs are the auroral component that caused it (see counterexample in Kimura et al., 2015, associated with internally driven reconfigurations), the spatially resolved enhancements of the MEs 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.

Two recent MHD simulations of the response of the Jovian magnetosphere and aurorae showed contrasted results. The Chané et al. (2017) simulation shows a brightening of the MEs at all local times, which is compatible with the observations of brightened MEs but contrary to expectations from the CE theory. On the other hand, Sarkango et al. (2019) found that the field-aligned currents decrease on the dayside, in accordance with the CE theory, but incompatible with the observed brightening of the MEs from HST. It should be noted that MHD simulations are complex tools, modeling more processes that just the corotation enforcement currents, and it is often difficult to disentangle which elementary process is causing which specific feature in the model output. Moreover, the fact that the two simulations provide contradictory results indicates that the chosen set of hypotheses, numerical schemes, and boundary conditions might considerably affect the end result.

2.5. Brightness Variations as a Response to Magnetic Loading/Unloading

Yao et al. (2019) directly compared the azimuthal and radial stretching of the dawnside 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 MEs in particular were brighter than during quiet times. It should be noted that the auroral morphology was distinct from dawn storms, the latter being probably associated with large-scale tail reconnection (Bonfond et al., 2020; Yao et al., 2020). They also noted that the stretching of the magnetic field or, in other words, the loading of energy in the magnetic field, oscillated during this interval. And, contrary to widely accepted theoretical expectations, the aurora and the radio kilometric emissions increased during the magnetic unloading phases, as if the magnetic energy was converted into particle energy, similarly to what is observed on Earth.

2.6. Quasi-Static Potentials Are Not the Main Driver for the MEs

One of the main findings of the Juno mission so far is the ubiquity of 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 MEs at Jupiter are even brighter and more permanent, it was thought that such quasi-static potentials would also dominate the energization of the charged particles. Such quasi-static potentials have 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 bidirectional 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 bidirectional electron acceleration appears to be the norm, the UV auroral brightness, which is almost solely related to the precipitating 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 bidirectional 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 coexist at different altitudes on the same field line. Thus, the presence of UV aurora is not even a sure indication of up-going currents.

3. Conclusions

It is not expected that 1-D (quasi)stationary models can 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 from these models and a number of them are challenged by measurements. While adopted by most models, hypotheses such as symmetry or steady state are not formally required by the corotation enforcement theory. However, these assumptions quickly show their limits in the case of Jupiter and models attempting to account for local time variations (Ray et al., 2014; Vogt et al., 2020) or time variability (Cowley et al., 2007) provided predictions opposite to observations. It is noteworthy that most of the observations mentioned above concern the generation of the auroras, which are associated with, but not strictly equivalent to, the magnetosphere-ionosphere coupling processes and their related currents. After all, such a coupling should exist since the magnetospheric plasma at Jupiter is rotating, and field-aligned currents have indeed been observed. While some of the evidence cited above concern widely used hypotheses, namely, local axisymmetry and quasi-static potential, which are not strict requirements of the corotation enforcement concept, others, such as the response to the solar wind changes and the dawn/dusk auroral brightness asymmetry challenge the theory in a more fundamental fashion. Thus, it is not clear yet whether the question of the origin of the MEs at Jupiter requires some adjustments of the widely accepted theory, the addition of other equally important mechanisms to the global explanation 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 (locally) axisymmetric models is limited at Jupiter, as local time effects, fragmentation phenomena, and nonaxisymmetric current systems are critically important. Finally, the findings reported 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). Moreover, other plasma waves (auroral hiss) have also been suggested as being important in the acceleration of energetic particles in Jupiter's polar region and may also be relevant for the MEs (e.g., Elliott et al., 2018; Kurth et al., 2018). 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 MEs.

Data Availability Statement

The data included herein are archived in NASA's Planetary Data System (https://pds-atmospheres.nmsu.edu/data_and_services/atmospheres_data/JUNO/juno.html).

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