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Periodic shearing motions in the Jovian magnetosphere causing a localized peak in the main auroral emission close to noon

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ABSTRACT

Recently, a transient localized brightness enhancement has been observed in Jupiter's main auroral emission close to noon by Palmaerts et al. (2014). We use results from three-dimensional global MHD simulations to understand what is causing this localized peak in the main emission. In the simulations, the peak occurs every rotation period and is due to shearing motions in the magnetodisk. These shearing motions are caused by heavy flux-tubes being accelerated to large azimuthal speeds at dawn. The centrifugal force acting on these flux-tubes is then so high that they rapidly move away from the planet. When they reach noon, their azimuthal velocity decreases, thus reducing the centrifugal force, and allowing the flux-tubes to move back closer to Jupiter. The shearing motions associated with this periodic phenomenon locally increase the field aligned currents in the simulations, thus causing a transient brightness enhancement in the main auroral emission, similar to the one observed by Palmaerts et al. (2014).

1. Introduction

At Jupiter, the main auroral emission is located at about 15° magnetic colatitude on both hemispheres. This very bright (it can reach intensities of MR) emission is continuously present, relatively steady, and corotates with the planet (it is fixed in system III longitude). The main emission is clearly visible in ultraviolet, in visible light, and in thermal infrared (see Clarke et al., 2004; Badman et al., 2015; Grodent, 2015, and references therein). Radioti et al. (2008), using observations from the Hubble space telescope (HST), showed that the main emission displays a discontinuity fixed in magnetic local-time, between 08:00 LT and 13:00 LT, where the intensity of the emission is lower.

The main auroral emission has been shown to be generated by the breakdown of corotation of the plasma located at a radial distance of about 25 R_J in the magnetodisk. The large majority of the plasma inside Jupiter's magnetosphere originates from the volcanic moon Io, or from the neutral cloud associated with this moon. Close to Jupiter, the Iogenic plasma rigidly corotates with the planet and slowly moves away to larger radial distances. Eventually, this plasma is ejected in the magnetotail of Jupiter. While moving to larger radial distances, in the absence of external forces, the plasma angular velocity would decrease due to the conservation of angular momentum. This is not the case close to Jupiter, where strong magnetic Lorentz forces accelerate the plasma up to rigid corotation. At a given radial distance —that might be time-dependent and that can also depend on local-time— the Lorentz forces are not strong enough to accelerate the plasma up to rigid corotation: the plasma starts to sub-corotate. This is called the breakdown of corotation and it affects the shape of the magnetic field lines, which begin to bent in the azimuthal direction (since the feet of the field lines rotate faster than their appexes). This bent back of the field lines produces a radial electrical current, which is closed via an equatorward Pedersen current in the ionosphere and via field aligned currents between the ionosphere and the magnetodisk. The strong field aligned currents accelerate electrons to very high speeds towards the ionosphere, generating the main auroral emission (which thus maps to the position of the corotation breakdown). This phenomenon was first explained by Bunce and Cowley (2001); Cowley and Bunce (2001); Hill (2001).

Recently, Palmaerts et al. (2014) used HST UV observations of the-Jovian main auroral emission and found a transient localized brightness enhancement of the main emission close to noon local-time (see Fig. 1). This small scale feature was observed on both hemispheres. Statistical analysis showed that this enhancement was localized between 10:00 LT and 15:00 LT in the southern hemisphere and between 09:00 LT and 15:30 LT in the northern hemisphere. Palmaerts et al. (2014) found that

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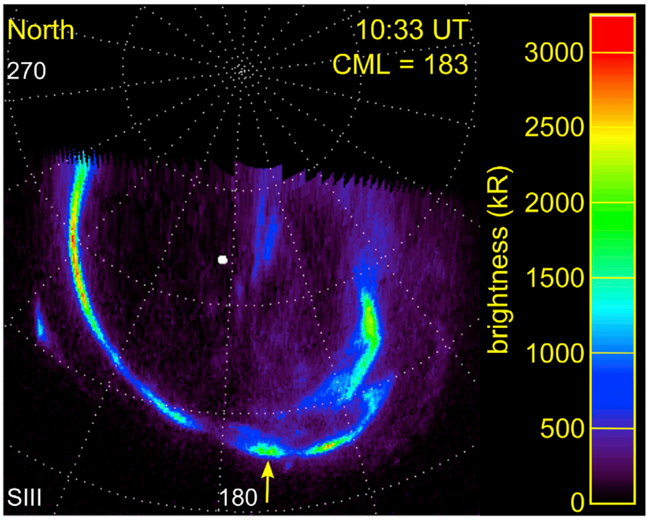

Fig. 1. Polar projection in System III polar coordinate system of an auroral image obtained with the Advanced Camera for Surveys (ACS) of the Hubble Space Telescope on February 7, 2006. System III 180° meridian and the magnetic local noon are oriented toward the bottom of the page. The transient localized auroral peak is indicated by the yellow arrow. Further information about this image and the whole sequence of observation can be found in Palmaerts et al. (2014) where this image comes from. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

the brightness of this localized peak can be 4.6 times larger than the average main emission. This localized peak in the main auroral emission is also present in global MHD simulation by Chané et al. (2013, 2017). It is observed in all simulations and occurs naturally. In the present paper, we will analyze in details simulation 2 of Chané et al. (2017) in order to understand what is causing this localized peak in the main emission in the simulations.

2. Numerical setup

The numerical setup was already presented in details in Chané et al. (2017) (in the present paper, we simply re-analyze simulation 2). Nevertheless for the reader convenience, we give below a summary of this numerical setup. Our simulations are global three dimensional one-fluid MHD simulations of the interaction between the solar wind and Jupiter's magnetosphere. We use the code MPI-AMRVAC to solve the equations (see Keppens et al., 2012; Porth et al., 2014; Xia et al., 2018). The details of the model can be found in Chané et al. (2013). The equations solved in the model are the ideal MHD equations plus gravity. In addition, in an axisymmetric toroidal region representing the Io torus, a mass-loading source term is added to the equations. The total mass-loading in the torus is set to 1000 kg/s, and it is assumed that the neutral particles have a Keplerian velocity prior to ionization. The magnetosphere-ionosphere coupling is also introduced as a source term in the MHD equations, namely by including ion-neutral collisions in an axisymmetric region above the inner boundary. These collisions accelerate the plasma in the ionospheric region (thus initiating the rotation of the magnetosphere) and allow for electrical current closure (since the collisions generate finite Pedersen and Hall conductivities in the ionospheric region). It is assumed that the neutral particles in the ionosphere are rigidly corotating with Jupiter.

In our simulations, the inner boundary is located at 4.5 $\mathrm{R_J}$ and the outer boundary at 189 $\mathrm{R_J}$. The inner boundary is not at 1 $\mathrm{R_J}$, because the time-step is limited by the Courant-Friedrichs-Lewy (CFL) condition: at 1 $\mathrm{R_J}$ the Alfvén speed is so large that the time-steps would be too small to perform the simulations in a reasonable amount of time. Note that in other global simulations of the Jovian magnetosphere published in the literature, the inner boundary is located even farther (the closest being 8 $\mathrm{R_J}$ in Moriguchi et al., 2008). In our simulations, the ionospheric region is unrealistically large (between 4.5 and 8.5 $\mathrm{R_J}$) because the numerical resolution is too coarse to simulate a smaller ionospheric region and because increasing the numerical resolution would slow down the simulation too much. Finally, in order to have a clear separation between the torus and the ionospheric region, the mass-loading cannot occur at the orbit of Io (5.9 $\mathrm{R_J}$). We therefore place the mass-loading in a torus of large radius 10 $\mathrm{R_J}$ and of small radius 1 $\mathrm{R_J}$ (thus between 9 $\mathrm{R_J}$ and 11 $\mathrm{R_J}$). The drawback is that our model is not realistic close to the inner boundary (the ionosphere is too large and the Io torus is too far). The main advantage is that the magnetosphere-ionosphere coupling occurs inside the numerical domain, above the inner boundary (not through the boundary like in other models), precluding any spurious effect at the boundary to affect the coupling. This magnetosphere-ionosphere coupling has been extensively tested in Chané et al. (2013), where it was shown to give realistic results, in agreement with both theories and observations. Therefore, the aforementioned restrictions will not affect the results of the present study.

The solar wind parameters used in this simulation are the following: $v_x = -400$ km/s, $v_y = v_z = 0$, $B_y = 0.44$ nT, $B_x = B_z = 0$, $T = 15\,000$ K; with $\rho = 0.162$ amu cm^{-3} for $t < 0$ and then $\rho = 0.552$ amu cm^{-3} for $t \geqslant 0$ (i.e. the time $t = 0$ is defined as the instant when the high density solar wind reaches the magnetosphere). Note that during the first 328 h of the simulation (when $t < 0$ and $\rho = 0.162$ amu cm^{-3} in the solar wind), the simulation reaches a quasi steady state. Although the outer boundary – located at 189 $\mathrm{R_J}$ – is spherically shaped, the plasma density increase (by a factor of 3.4) is introduced in a plane-parallel structure. It should also be noted that the solar wind density is linearly increased during a time interval of 1 h. It means that at a given time, the imposed density at the outer is not uniformed: it can be 0.162 amu cm^{-3} for $x < x_1$, 0.552 amu cm^{-3} for $x > x_2$ (where x_1 and x_2 are the positions where the transition between low density and the high density solar wind occurs), and decrease linearly in between. The simulations are performed on a static mesh, where three levels of refinement are used. The smallest cells are 0.25 $\mathrm{R_J}$ large and the largest cells 1 $\mathrm{R_J}$ large. The effective resolution is 800×128×128. This mesh is the same as the one used for all the simulations in Chané et al. (2017). In the simulation, both the rotational and the magnetic axes are aligned with the z-axis.

3. Localised peak and shearing motions

In this section, we will show that the localized peak in our simulations is associated with shearing motions in the magnetodisk. The central panels of Fig. 2 illustrate the periodic formation of this localized peak of electrical current in the ionosphere around noon local-time in all our simulations. Every rotation period, the ionospheric field aligned currents are locally enhanced around noon. In our simulations, the ionospheric field aligned current are strongest on the night side, and display a minimum on the prenoon sector. This minimum corresponds to the main oval discontinuity observed by Radioti et al. (2008). As discussed by Chané et al. (2017), the field aligned currents are stronger on the night-side because the field lines are more elongated at that location. As a result, this is also where azimuthal bending of the field lines due to subcorotating plasma generates the largest radial electrical currents (which are closed in the ionosphere via field aligned currents). Fig. 2 shows that, in our simulation, $j_{\parallel}/B$ close to noon increases by 60% within 5 h before returning to lower values 5 h later. Fig. 3 displays $j_{\parallel}/B$ in our simulation, in the ionosphere when the localized peak is present (at time $t =$25h00). The main emission discontinuity (between 8:00 LT and 15:00 LT) and the localized peak (around 13:00 LT) are clearly visible in this figure.

The left panels of Fig. 2 show that in our simulations, the periodic localized peak in ionospheric field aligned current is associated with an inward motion of the plasma on the day-side magnetodisk. At time $t =$20h00, there are almost no inward motions of plasma visible inside