Quasi-periodic polar flares at Jupiter: A signature of pulsed dayside reconnections?

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[1] The most dynamic part of the Jovian UV aurora is located inside the main auroral oval. This region is known to regularly show localized but dramatic enhancements on timescales of several tens of seconds, called polar flares. They have often been associated with the polar cusp, based on their location in the polar cap. The present study is based on the longest high-time resolution image sequences ever acquired by the Space Telescope Imaging Spectrograph aboard the Hubble Space Telescope. We report the first observations of a regularity in the occurrence of these flares, with a timescale of 2–3 minutes. We use a magnetic flux mapping model to identify the region corresponding to these emissions in the equatorial plane: the radial distance ranges from 55 to 120 Jovian radii and the local times are between 10:00 and 18:00. The analogy with similar phenomena observed at Earth suggests that these quasi-periodic auroral flares could be related to pulsed reconnections at the dayside magnetopause. Indeed, the flares' projected location in the equatorial plane and their rate of re-occurrence show some similarities with the properties of the flux transfer events observed by the Pioneer and Voyager probes.

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1. Introduction

[2] Polar emissions are the most variable component of the Far Ultraviolet (FUV) Jovian aurora. They are located poleward of the two other principal components, i.e. the main emissions, which are usually associated with corotation breakdown of magnetospheric plasma, and the satellite footprints. *Grodent et al.* [2003b] subdivided these polar emissions into three distinct regions. The most polar one is the swirl region, consisting of faint patchy emission features. On the dawn side lies the dark region, nearly devoid of FUV emissions. The third region is the active region, which is located around noon in magnetic local time and is the locus of bright arc-like features and flares. Doppler-shifted H_3^+ infrared emissions indicate that this region of the ionosphere, also called the Bright Polar Region, is corotating with the planet [*Stallard et al.*, 2003]. The intensity of these transient and localized FUV emissions can increase by a factor of 30 within ~1 minute to reach a peak brightness as large as ~40 MR [*Waite et al.*, 2001]. These features appear to map to the outer (i.e. beyond 30 Jovian radii) dayside magnetosphere, and *Pallier and Prangé* [2001, 2004] identified this region as the Jovian polar cusp. They also showed that cusp emissions below 1450 Å were strongly attenuated by methane absorption, leading to 'electron-equivalent' energies of ~200 keV. However, electrons are not the only charged particles able to produce these features: ion precipitation could also be the cause of the FUV emissions. Based on XMM-Newton observations, *Branduardi-Raymont et al.* [2008] showed that the X-ray photons with energies below 2 keV, i.e. those consistent with precipitation of highly stripped ions, were preferentially originating from the active region.

[3] All the FUV time-tag sequences acquired with the Space Telescope Imaging Spectrograph (STIS) aboard the Hubble Space Telescope (HST) before its failure in 2004 were only 5 minutes long at maximum. The refurbishment of STIS in 2009 made it possible to acquire 45 minutes long time-tag sequences, providing, for the first time, high time resolution observations over a complete HST orbit.

2. Data Processing

[4] The present study is based on time-tag observations of the southern hemisphere of Jupiter performed with STIS during two HST observation orbits from the GO-11649 program, on 31 August and 11 September 2009 respectively. The central meridian longitude (CML) ranged from 107° to 134° during the August orbit and from 79° to 105° during the September orbit. During this campaign, a second sequence was also acquired on 31 August, but the observation geometry of this particular sequence prevented a good visibility of the polar region. The strontium-fluoride filter, which cuts off most of the Ly-α emissions, was used in order to avoid contamination by geocoronal emissions. Following *Grodent et al.* [2003a], we assume that 1 count/s corresponds to a brightness of 1975.5 kR and to an emitted power of $d^2/(2.54\ 10^9)$ W where d is the Earth-Jupiter distance in km.

[5] In order to study the brightness and the emitted power of the various polar emissions, we removed an empirical planetary disk background. This extrapolation of the planetary disk is based on the evolution of the brightness with latitude and longitude on images acquired with the F165LP filter on the HST Advanced Camera for Surveys. This filter transmits the emissions from the planetary disk as seen on the unfiltered FUV images, but blocks most of the auroral emissions. In the polar region, the brightness of the disk a

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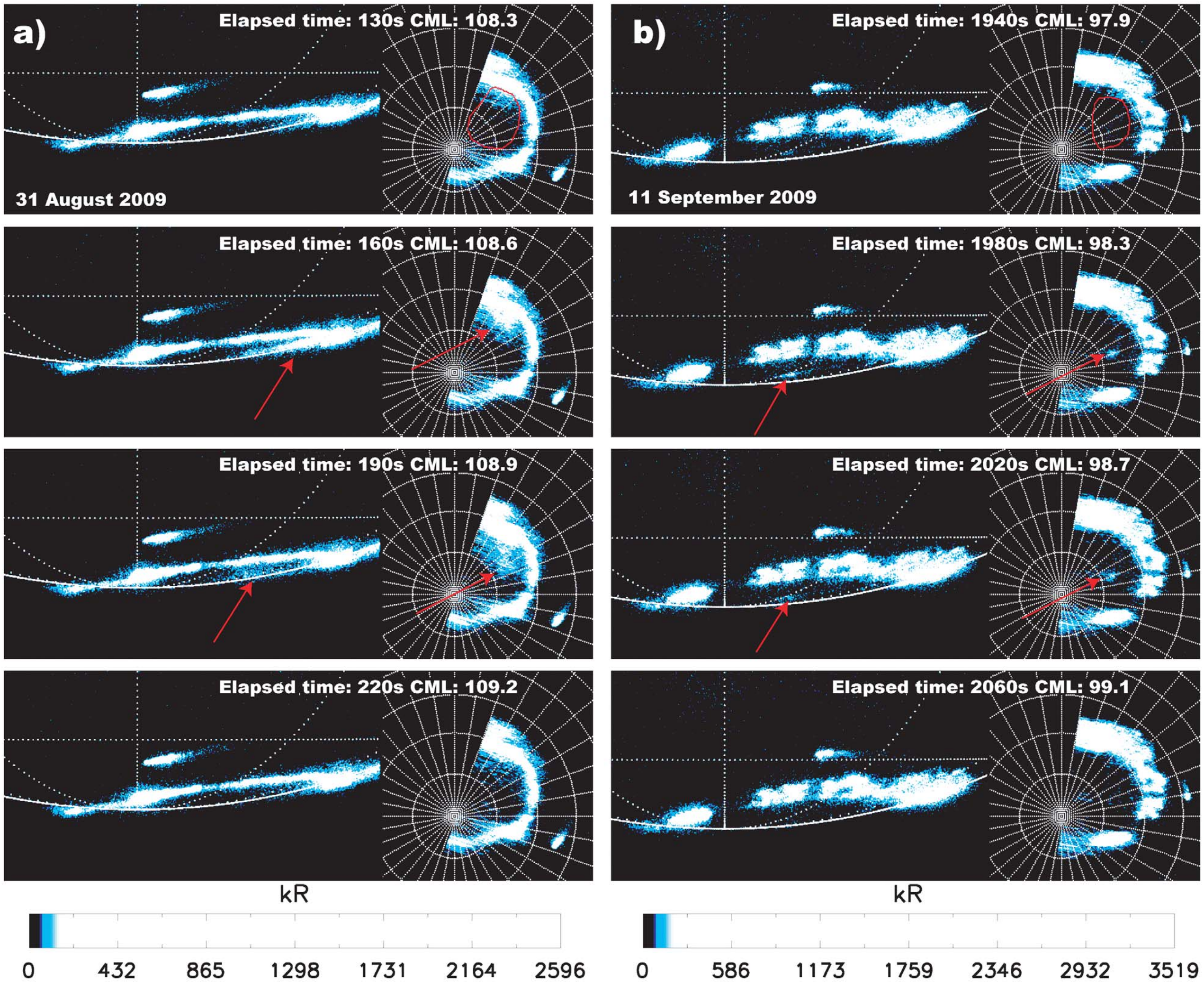

Figure 1. (a) Sequences of images of the southern Jovian aurora acquired 30 seconds apart during the 31 August 2009 HST orbit. The polar projections corresponding to these images is shown directly on the right. (b) Sequences of images of the southern Jovian aurora acquired 40 seconds apart during the 11 September 2009 orbit. The area defined as the active region is highlighted in red in the first images.

few degrees inside the limb does not vary with the latitude. On the other hand, along a given meridian line, the brightness decreases linearly towards the pole. The extrapolation of the polar disk in the auroral regions thus consists in considering the brightness along the 53°S parallel line (i.e. in the polar region, but outside the auroral emissions), and then interpolating between these values and the limb brightness along the meridians.

3. Characteristics of the FUV Flares

[6] Figure 1 shows time series extracted from both 45-minute sequences. In each case, the first column displays the original images with the background disk removed while the second column displays the polar projections. It is noticeable that the evolution of the flare morphology is different for the two cases. In the first case (CML 107°–134°), the flare starts close to the dusk side of the main emission and rapidly propagates dawnward. In the second sequence (CML 79°–105°), the flare appears in the center of the polar region and typically spreads over ~3000 km (with a maximum extent up to ~8000 km), then it recedes and finally disappears.

[7] Figure 1 shows only two examples of flares, however the 45 minutes long sequences clearly demonstrate that the flashes repeat regularly (see auxiliary material[1] Animations S1 and S2). The evolution of the emitted power in the active region is shown in Figure 2a. The active region has been defined manually on the superposition of the polar projections as the brightest part of the polar region. From one frame to another, the surface is kept fixed in System III, and thus evolves on the HST images due to the rotation of the planet. In both cases, the flares lead to a power in excess of ~10–40 GW compared to the quiet configurations. One way to visualize the regularity of the flares is the histogram of the inter peak intervals (Figure 2b). From these plots, it is noticeable that the mean inter-peak time interval is slightly longer in the second case (~160 seconds), than in the first one (~120 seconds). Another method to study the quasi-

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2010GL045981.

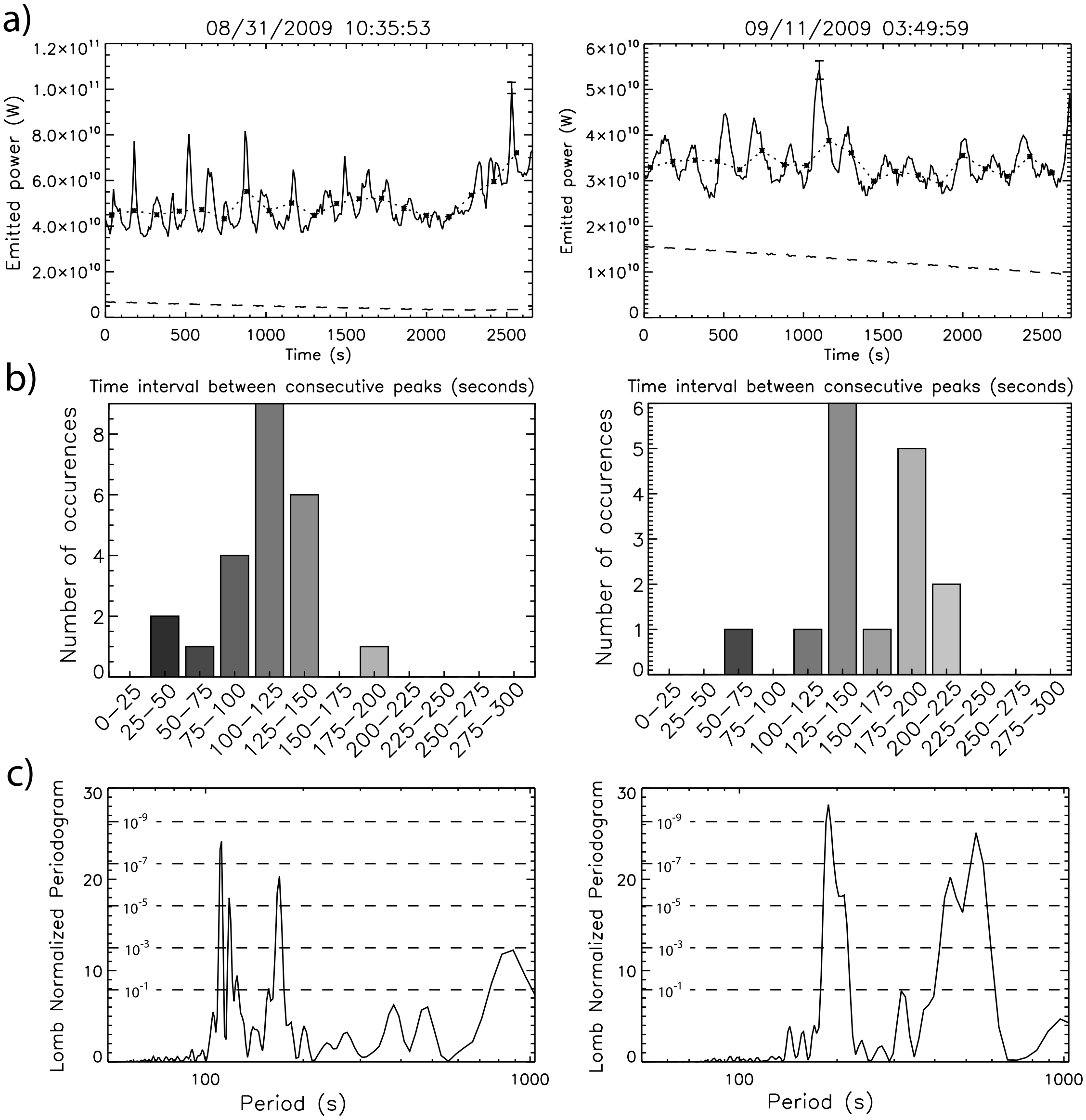

Figure 2. (a) The evolution of the emitted power inside the active region for the two sequences. The excess of emitted power caused by the polar flares is on the order of 10–40 GW. The dashed line represents the subtracted disk background in the area under consideration. The error bar represents the 2σ uncertainty on the count rate. The dotted line represents the evolution of the polar region that would have been observed for a typical observation strategy without the time-tag mode. (b) Histograms of the time interval between two consecutive brightness peaks, which are defined as the local maxima of the power curve smoothed over 50s. The typical timescale is between 100 and 200 seconds. (c) Represents the Lomb periodograms for the two sequences. The low frequencies caused by the evolution of the contamination from the main auroral emissions have been removed before performing the Lomb analysis. The dashed lines represent the significance levels.

periodicity of the flares is the Lomb analysis. On the periodograms shown on Figure 2c, the peaks corresponding to the most significant periods are ~110 s and ~170 s in the first case, and ~190 s and ~540 s in the second one. The first three all belong to the same 2–3 minutes range while the fourth one could possibly correspond to an undertone frequency since the period ratio is ~3.

[8] Additionally, we localized the point where the flares appear. In order to determine the magnetospheric region corresponding to these flares, we made use of a model based on the flux mapping approach (M. F. Vogt et al., Improved mapping of Jupiter's auroral features to magnetospheric sources, submitted to *Journal of Geophysical Research*, 2011). This method determines the correspondence between regions in the equatorial plane and their ionospheric counterparts by balancing the magnetic field flux as measured by *in-situ* spacecrafts and the estimated magnetic fluxes at the surface of Jupiter. We found that in each case, the flares correspond to a region in the equatorial plane which is consistent with the expected magnetopause location in an expanded state (Figure 3). The accuracy of the model is not optimal in this region due to a lack of observational

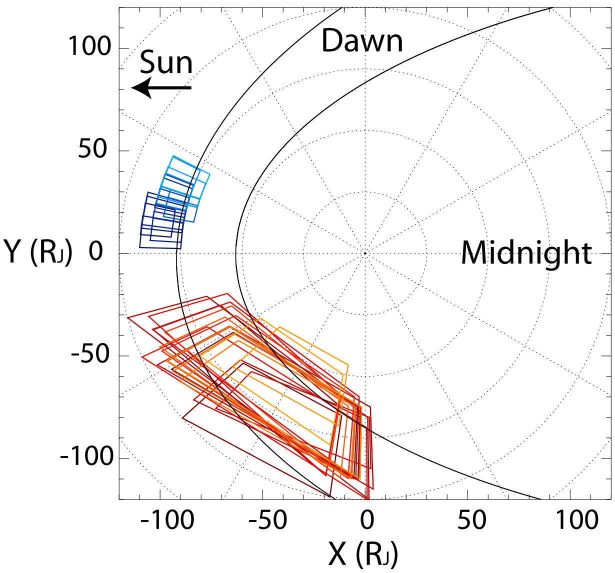

Figure 3. Equatorial view of the mapping of the appearance points of the flares in the equatorial plane, according to the magnetic field model from M. F. Vogt et al. (Improved mapping of Jupiter's auroral features to magnetospheric sources, submitted to *Journal of Geophysical Research*, 2011). The red boxes correspond to the 31 August sequence and the blue boxes correspond to the 11 September sequence. The solid lines represent probable magnetopause locations for extended ($92R_J$) and compressed ($63R_J$) magnetosphere cases [*Joy et al.*, 2002]. The extent of the boxes is essentially the consequence of the large positioning uncertainty due to the proximity to the limb. Note that the size of the box is an estimate of the geometric uncertainty and not the mapping of the flares' surface.

constraints, however, we believe that most of the overall uncertainty is a consequence of the limited accuracy of the localisation of the points on the images when the features are too close to the limb. The radial distance ranges from 55 Jovian radii (R_J) to 120 R_J in the first case and from 85 R_J to 110 R_J in the second case. As far as the azimuthal locations are concerned, they range from 13:00 LT to 18:00 LT in the first case and from 10:00 LT to 12:00 LT in the second case.

[9] In the sequence acquired in August (Figure 1a), the flares emerge on the dusk side of the polar region and propagate towards dawn at an apparent speed of ~150 km/s (~6000 km in 40 seconds). Since these emissions are very close to the limb, only limited information may be deduced on their exact location and motion along the line of sight. Consequently, our calculation assumes that the flare is moving along the limb plane, which results in a minimum value of the velocity. When mapped into the equatorial plane, the flare region appears to move by ~3 hours in local time within 40 seconds, which would be equivalent to a velocity of ~115000 km/s at a radius of 85 R_J.

4. Discussion and Conclusions

[10] The UV auroral observations presented here are not the first ones to report periodicity in the auroral emitted power. Observations of Jovian X-ray emissions by the Chandra telescope already revealed some periodicities in the count rates originating from the active region and ranging from ~30 to ~65 minutes [*Gladstone et al.*, 2002; *Elsner et al.*, 2005]. *Pryor et al.* [2005] reported the finding of a quasi-periodic enhancement of the Jovian UV auroral emissions on timescales of ~10 minutes. However, the spatial resolution of these observations performed with the UVIS instrument onboard the Cassini spacecraft did not permit the authors to identify the region causing these effects. With the 2009 HST sequences, we are able to locate without any ambiguity quasi-periodic brightenings in the active region. The reason why this short quasi-periodicity was not found in previous HST data stems from the limited duration of the previous time-tag sequences [e.g., *Waite et al.*, 2001] or to the insufficient sampling rate for the ACCUM images. The dashed curve on Figure 2a shows the light curve which would have been observed with the same observation strategy as the GO 10862 campaign in Spring 2007, i.e. nineteen 100-second exposure time images within 45 minutes.

[11] The pulsating emissions appear to map to the dayside magnetopause, indicating that these flares most probably correspond to the cusp region [*Bunce et al.*, 2004; *Pallier and Prangé*, 2004]. On Earth, strong fluctuations of the proton related cusp emissions with a quasi-period of ~8 minutes have been observed during component reconnections with a southward interplanetary magnetic field. This phenomenon has been associated with the characteristic period of flux transfer events (FTEs) related to pulsed reconnection [*Fuselier et al.*, 2007]. FTEs signatures have also been observed at Jupiter during the two Pioneer and the two Voyager flybys [*Walker and Russell*, 1985]. The re-occurrence of FTEs at Jupiter has been measured to lie between 1 and 4 minutes, which is fairly similar to the inter-flare intervals discussed in the present study. As a consequence, both the involved timescales and the mapped location of the flares suggest that they could be related to pulsed reconnections and FTEs on the dayside magnetopause. Another noteworthy similarity between the cusp emissions at Earth and the active region at Jupiter is that they both involve ion precipitations, as shown by *Branduardi-Raymont et al.* [2008].

[12] In order to scale the 8 minutes FTE periodicity from the Earth up to the size of the Jovian magnetopshere, *Bunce et al.* [2004] proposed to use the Alfvén transit time between the two hemispheres at the dayside magnetopause. This time interval is around 40 minutes at Jupiter and could correspond to the time required for some feedback between the ionosphere and the magnetosphere. This timescale is indeed quite close to the 45 minutes X-ray period [*Gladstone et al.*, 2002] or the 40 minutes period of the quasi-periodic radio emissions [*MacDowall et al.*, 1993] and electron bursts [*McKibben et al.*, 1993] observed by Ulysses. However, later observations from the Galileo and Cassini spacecraft identified quasi-periods ranging from <1 minute to 1 hour, including periods of 2–3 minutes [*Hospodarsky et al.*, 2004]. It should also be noted that a 2–3 minutes periodicity has also been found in electrons bursts detected by Ulysses [*McKibben et al.*, 1993]. Together with these observations, the auroral pulsations suggests that this period is another important timescale in the Jovian magnetosphere. If the quasi-period of the UV flares is related to the periodicity of dayside reconnections, then our observations

question the importance of the magnetosphere-ionosphere coupling in controlling their occurrence rate. Additionally, the fact that FTE periods are also present at Mercury, where a significant ionosphere does not exist, also indicates that the appearance of FTEs is probably a product of the magnetopause itself and that the presence of an atmospheric feedback is not a necessary ingredient for pulsations to occur [*Russell*, 2000].

[13] One of the more puzzling results of our observations is the very fast dawnward motion of the flares in the 31 August sequence. In the ionosphere, the apparent velocity of the flares is two orders of magnitude faster than the ionospheric flow velocities [*Stallard et al.*, 2003] and can thus hardly be explained by ionospheric convection. By analogy with the longitudinal motion of the proton cusp on Earth, the apparent motion could be related to changes in the dawn-dusk component of the interplanetary magnetic field [*Phan et al.*, 2003]. On the other hand, this dusk to dawn motion of the flares bears some similarities with the spatial evolution of the poleward moving auroral forms (PMAFs) at the Earth, which are also associated with FTEs. *Milan et al.* [2000] attributed their apparent azimuthal motion to the expansion of the reconnection X-line, i.e. to a sweeping of the reconnection site. In our case, this interpretation could explain the very fast apparent propagation of the emission region, since it does not necessitate any actual motion, but only requires that reconnection takes place at different places through time.

[14] Finally, it should be noted that this quasi-periodic behavior has only been studied for two cases. More observations with high time resolution are required to investigate whether the quasi-periodic flares are general or particular cases and whether the quasi-period is consistently on the order of 2–3 minutes. Observations of such quasi-periodic flares in the northern hemisphere with central meridian longitudes close to 160°, offering a much better visibility of the polar regions, could considerably facilitate the study of the evolution of the shape, the size and the motion of the flares.

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