Variability of Jupiter's main auroral emission and satellite footprints

Scientific Category: Solar System
Scientific Keywords: Giant Planets, Planetary Atmospheres, Space Weather
Budget Size: Regular

UV Initiative: Yes

Abstract

Jupiter's UV auroral emissions are the brightest in the solar system. They include the main auroral emission, which is associated with a system of corotation enforcement currents, and patches of bright emission called the satellite footprints because they occur at the ionospheric end of field lines linked to Jupiter's moons Io, Europa, and Ganymede. Because the footprints' ionospheric positions are linked to a fixed radial distance in the magnetosphere, changes in the satellite footprint locations are likely due to changes in Jupiter's magnetospheric field configuration. Variability in the main emission location is more complicated by comparison because the main emission can be influenced both by the field configuration and by other factors related to the corotation enforcement current system. We propose to analyze HST images of Jupiter's UV aurora to quantify variability in the satellite footprint locations and main emission. Comparing the variability of these two features will establish the cause of shifts observed in Jupiter's main emission and will provide valuable constraints for models of Jovian magnetosphere-ionosphere coupling. This work is timely because it will provide a framework for the upcoming Juno mission, which will study Jupiter's polar regions. Our work builds upon previous studies of auroral variability but will be the first to focus on images from the Galileo era and make direct comparisons to magnetospheric variability observed in situ. This proposal supports the HST UV initiative and the proposed analysis was not included in the original GO proposals.

Investigators:

	Investigator	Institution	Country
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Number of investigators: 4
* ESA investigators: 1

Dataset Summary:

Instrument	No. of Datasets	Retrieval Method	Retrieval Plan
STIS	3	FTP	All datasets will be acquired over one week

- **Scientific Justification**

Auroral emissions are observed on planets and moons throughout the solar system and provide an excellent method for remotely sensing the local magnetic field plasma environment, which can vary dramatically from planet to planet. Jupiter's UV auroral emissions, produced by excitation of atmospheric H_2 and H by precipitating electrons, are the brightest in the solar system at more than 10^{14} Watts [e.g. Bhardwaj and Gladstone, 2000], due largely to Jupiter's intense planetary magnetic field, the strongest in the solar system. HST images of Jupiter's aurora show the presence of features like the main oval (or main emission) that appear similar to their terrestrial counterparts, though they are thought to be produced by different magnetospheric processes than those that drive the Earth's aurora. At the Earth, the aurora are driven by the solar wind and light up in response to solar storms, whereas the main auroral emission at Jupiter does display some variability with the external solar wind conditions but is mainly driven by processes internal to the magnetosphere. Jupiter's main auroral emission is associated with a system of corotation enforcement currents that arise in order to speed up plasma originating from the volcanic moon Io as the plasma moves radially outward and loses azimuthal velocity due to conservation of angular momentum [Cowley and Bunce, 2001; Hill, 2001].

In addition to the main emission, Jupiter's aurora features patches of bright emission that occur at the ionospheric end of field lines linked to Jupiter's moons Io, Europa, and Ganymede [Clarke et al., 2002], as shown in Figure 1. These satellite footprints provide key constraints in developing models of Jupiter's internal magnetic field [Connerney et al., 1998; Grodent et al., 2008b], because the satellite's orbital locations are known (Io at 5.9 R_J or Jovian radii, Europa at 9.4 R_J, and Ganymede at 15 R_J) and the mapping along magnetic field lines can be accurately traced from each moon to a specific location in the ionosphere.

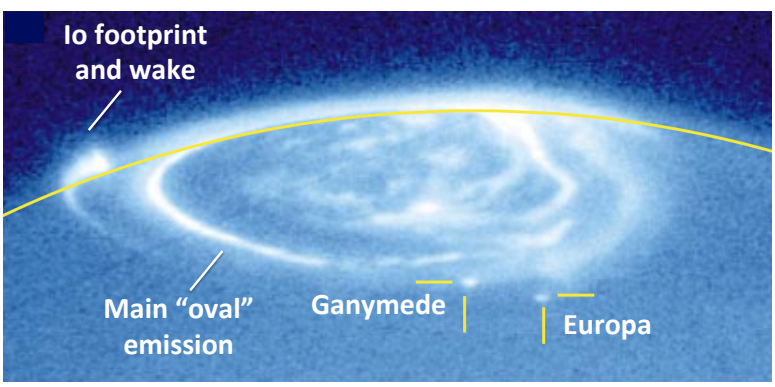

Figure 1. Composite of images taken with STIS UV-MAMA of Jupiter's northern aurora. The footprints of 3 of the Galilean satellites are clearly visible. Modified from Clarke et al. [2002].

Because their ionospheric positions are linked to a fixed radial distance in the magnetosphere, the satellite footprints enable mapping of the magnetic field and thus *any changes in their position provide valuable information about variability in Jupiter's magnetosphere*. For example, in the two HST images in Figure 2 the locations of the main auroral emission and the Ganymede footprint differ by a few degrees in latitude. The fact that the Ganymede footprint shifts suggests that the variability is changes in the local magnetic field configuration, which can be caused by changes in the current density of Jupiter's current sheet. The magnetic field in Jupiter's magnetosphere is largely dipolar inside of 10 R_J, while in the middle magnetosphere the presence of a current sheet stretches the field radially, as illustrated by

the red lines in Figure 2. Increased current sheet current density results in increasingly stretched field lines, which alters the ionospheric mapping of a fixed radial distance in the magnetosphere. Therefore, the locations of the satellite footprints with respect to their average locations are useful diagnostics for the strength of Jupiter's current sheet, which is related to the total plasma density and provides one metric by which we can measure the state of the magnetosphere.

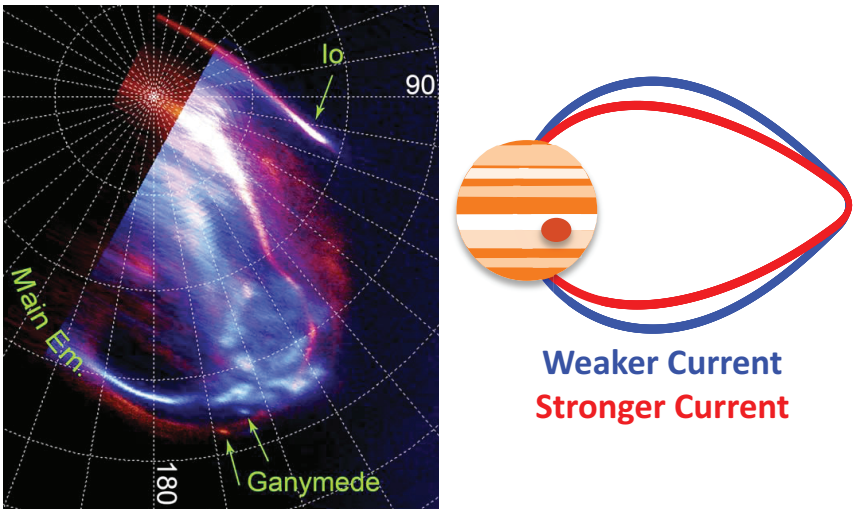

Figure 2. (Left) HST images of Jupiter's aurora from Dec. 2000 (red) and April 2005 (blue). From *Grodent et al.* [2008a]. (Right) Illustration of how two sample field lines with the same equatorial crossing distance can have different ionospheric mapping (not to scale). The red field line is less dipolar than the blue field line due to a stronger current sheet current density.

The goal of the proposed work is to understand the nature and drivers of temporal changes in Jupiter's magnetosphere and its main auroral emission. Variability in the main emission location is more complicated than for the satellite footprints because the main emission is influenced by factors other than just the degree of field stretching. The current system that drives the main emission features a radial current in the equatorial magnetosphere that generally peaks near 20-30 R_J, meaning that the main emission appears at the ionospheric footprint of field lines that map to those radial distances. This current system can be influenced by factors like the rate of plasma radial outflow from Io's orbit [e.g. Nichols, 2011], which can shift the peak of the radial current and therefore the radial distance mapping of the main emission. That means that the main emission can shift in latitude (higher latitudes map to larger distances) without a corresponding change in the field configuration or shift in the satellite footprints. An extreme example of this behavior can be seen in two images reported by Bonfond et al. [2012]. In both images the Ganymede footprint is located in same position, but the main emission is located poleward of the Ganymede footprint in one image and equatorward of the footprint in the other. Therefore, the satellite footprints provide a critical way of distinguishing whether shifts in the main emission are the result of a field reconfiguration or of a change in the corotation enforcement current system, or both.

We propose to analyze HST images of Jupiter's UV aurora to quantify variability in the satellite footprint locations and main emission. Our work will answer the following questions:

- **Do Jupiter's main emission and satellite footprints display similar variability?**
- **What is the cause of latitudinal shifts in Jupiter's main emission?**

We will answer these questions by analyzing the locations of the satellite footprints and main emission in HST images taken between 1996 and 2003, when contemporaneous *in situ* magnetospheric measurements collected by the Galileo spacecraft are available. These

magnetospheric datasets can provide context for the auroral observations, since Galileo has observed variability in Jupiter's current sheet [e.g. Russell et al., 2001] that will shift the satellite footprints as shown in Figure 2. Therefore we will focus on images from the Galileo era but will extend our analysis to more recent observing campaigns as appropriate. Our results will establish whether Jupiter's main emission shifts in response to changes in the magnetospheric field configuration or in the variable processes associated with the current system that drives the main emission, or some combination of both. As a specific example, when we observe similar variability (in both magnitude and direction) in both the main emission and the satellite footprints like that shown in Figure 2 we will conclude that this variability is most likely caused by a magnetospheric field reconfiguration. In cases where the main emission and satellite footprints do not display similar shifts we will be able to quantify how much of the main emission motion results from changes in the field configuration and how much results from changes in the corotation enforcement current system. This latter quantity will provide a valuable constraint for models of Jovian magnetosphere-ionosphere coupling [e.g. Nichols, 2011; Ray et al., 2014].

This work is timely because it will provide a framework for the upcoming Juno mission, which will study Jupiter's polar regions. Our work builds upon previous studies of the satellite footprints but will be the first to focus on images from the Galileo era and make direct comparisons to magnetospheric variability observed *in situ*. Features like the brightness and multiple spots of the Io and Ganymede footprints are well studied [e.g., Bonfond et al., 2007, 2009, 2012, 2013; Grodent et al., 2009]. However, many studies of the satellite footprints have focused entirely on data from the 2007 HST campaign [e.g. Bonfond et al., 2009, 2012], neglecting images from the Galileo era (1996-2003). Other studies have incorporated HST images from the Galileo era but have not quantitatively examined variability in the satellite footprint locations [e.g. Grodent et al., 2009]. <u>This proposal supports the HST UV initiative because it relies on analysis of HST UV images of Jupiter's aurora.</u>

• Analysis Plan

We will focus our analysis on STIS and ACS images taken between 1996 and 2003, when contemporaneous *in situ* magnetospheric measurements collected by the Galileo spacecraft are available. This time interval covers observing programs 7308, 8171, and 8657. There are roughly 253 STIS images that were taken between 1996 and 2003, as shown in table 1. The satellite footprints are not always visible in auroral images depending on each moon's location within its orbit, however a brief survey of images in the APIS database (http://apis.obspm.fr/) shows that at least 35 Galileo-era images include at least two clear satellite footprints (all include the main emission). Therefore, focusing on the Galileo era images initially should be sufficient for our study, but if our initial findings using the smaller dataset are not statistically significant we will apply our analysis to more recent observing campaigns, such as the ~200 ACS Jupiter images from observing program 10862 in 2007.

Table 1. HST observations to be used in this study (total 253 images)

Observing Program	Dates	Instrument	Number of images
7308	July 3, 1997 - Feb. 1, 2001	STIS	55
8171	Aug. 8, 1999 - Nov. 14, 2000	STIS	69
8657	Dec. 14, 2000-Jan. 21, 2001	STIS	129

Because the images will come from several different observing campaigns, all images will be reduced following the latest version of the BU pipeline process (see Clarke et al. [2009]). This process is well-established and tested, and includes a dark count subtraction, flat field response correction, interpolation over bad pixels, and other corrections and rotations necessary to identify the planet center and make a polar projection of each image. We will make use of the BU library of established IDL programs that can be used to perform navigation and photometry. For identifying the location of each satellite footprint and its uncertainty we will follow the analysis of Bonfond et al. [2009]. All Galileo-era data are available at BU through Co-I Clarke, who served as the PI on those observing campaigns, but where necessary we will access data from STScI via FTP.

We will begin by examining variability in the satellite footprint locations. Data from the magnetometer have been used to quantify changes in the Jovian current sheet during that era [Russell et al., 2001]. We have modeled how these changes are expected to affect the satellite footprints of Io, Europa, and Ganymede by fitting the Galileo observations with variable parameters in current sheet models [Vogt et al., 2013]. Our modeling predicts that the variability observed by Galileo is consistent with shifts in the Ganymede footprint by 0.7° in latitude from its average location. We will compare the observed satellite footprint locations to reference contours, or average locations, for the Io, Europa, and Ganymede footprints given by Grodent et al. [2008b]. When the footprints are equatorward (poleward) of the reference contours we expect the Galileo observations to show a stronger (weaker) than average magnetic field perturbation from Jupiter's current sheet. We will compare our predictions to the observed latitudinal shifts from the HST image to confirm our interpretation of the satellite footprint variability and provide context for the variability we observe in the main emission.

We will also examine the observed main emission location with respect to a reference contour [Nichols et al., 2009] to determine whether the main emission is shifted latitudinally, and will compare any main emission shifts to those of the satellite footprints. From this comparison we will determine the causes of temporal variability in Jupiter's main emission location. For example, if we observe a shift in the main emission that is similar in magnitude and direction (poleward or equatorward) to a shift observed in the satellite footprints (particularly Ganymede), like that shown in Figure 2, we will conclude that the most likely explanation is a field reconfiguration due to variability in Jupiter's current sheet. Conversely, if we observe a shift in the main emission without a corresponding shift in the satellite footprints we will conclude that the most likely explanation is a change in the variable processes associated with the current system that drives the main emission.

Finally, we acknowledge that our results will be sensitive to uncertainties in the planet center identification because our analysis involves identifying positions (latitude and longitude) of various auroral features. The expected error is smallest in the north-south direction (1-2 pixel uncertainty), which is more relevant to our work than the east-west direction (~few pixel uncertainty) because we are primarily concerned with latitudinal changes in the main emission and satellite footprints. This 1-2 pixel uncertainty should be sufficiently small to allow for precise identification of the main emission and satellite footprint locations with respect to the relevant reference contours or average positions. This information is necessary to calculate the absolute shifts of the main emission and satellite footprint. However, if the uncertainties associated with the planet center finding turn out to be significantly larger than expected, we can adjust our analysis plan to focus instead on calculating the distance between the Io or Ganymede

footprints and the main emission, which will not require such precise location identification. For example, if the Ganymede footprint-main emission distance is relatively constant then we can infer that the footprint and main emission display similar variability, even if we cannot precisely quantify that variability. This situation would be similar to that shown in Figure 2, and we could conclude that the variability is likely due to changes in the field configuration. However, if we observe the Ganymede footprint-main emission distance shrink or grow then we can conclude there was likely a significant change in the variable processes associated with the current system that drives the main emission.

• Management Plan

PI Luke Moore will be responsible for the management of this investigation and compliance with all reporting requirements. He has years of experience in modeling the plasma environment of Saturn, which is similar to Jupiter's [e.g., *Moore et al.*, 2004, 2014; *Moore and Mendillo*, 2005]. **Co-I Marissa Vogt** will be responsible for the day-to-day work and interactions with the graduate student. Her research has focused on Jupiter's magnetosphere and aurora [*Vogt et al.*, 2010, 2011, 2013, 2014a, 2014b, 2015], including modeling the temporal variability of the Jovian current sheet and its effects on Jupiter's aurora. Co-I Vogt is fully funded through March 2018 by an NSF postdoctoral fellowship. **A Boston University graduate student** will work under the guidance of Co-I Vogt. The student will analyze HST images to identify the positions of the Galilean satellite footprints and main auroral emission and determine their variability. **Co-I John Clarke** will advise on the analysis and interpretation of HST auroral images. He is one of the world's leading experts on conducting and analyzing HST UV observations of Jupiter's aurora [*Clarke et al.*, 1998, 2002, 2004, 2005, 2009]. Clarke served as a PI on GO programs 7308, 8171, 8657, and 10862. The goals of this archival research proposal are significantly different from the goal of those programs, which did not specifically address comparing variability in the main emission to that of the satellite footprints. **Co-I Bertrand Bonfond** will advise on the interpretation of HST auroral images. He is one of the world's leading experts on the Galilean satellite footprints [*Bonfond*, 2012; *Bonfond et al.*, 2007, 2009, 2012, 2013].

We will request funding for the graduate student to attend a professional meeting such as the bi-annual Magnetospheres of the Outer Planets meeting (to be held in 2017 in Uppsala, Sweden). This meeting will offer the graduate student a chance to present the results to the scientific community, receive feedback, and to interact directly with Co-I Bonfond. Most interactions with Co-I Bonfond will be conducted over email or video conference, but we will request funds for the graduate student to visit Co-I Bonfond once during the project. We will also request funds to cover publication costs so that the results of this research may be published in a high-impact journal.

Table 2. Proposed Schedule

Time	Task	Personnel
Months 1-4	Image processing with BU pipeline to create polar projections	Graduate student, Clarke, and Vogt
Months 5-7	Identification of satellite footprint locations	Graduate student, Bonfond, Vogt
Months 8-10	Identification of main emission location and comparison to reference oval	Graduate student, Clarke, Vogt
Months 10-12	Model expected satellite footprint locations for comparison to observations	Graduate student, Vogt
Months 13-15	Compare satellite footprint locations to main emission	Graduate student, Vogt
Month 16	Present initial results at professional meeting	Graduate student
Months 17-18	Write up manuscript describing results	All

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