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Key Points:

- We compared Jupiter's auroral variability from HST images to concurrent measurements of magnetospheric activity from the Galileo spacecraft
- We found that the Ganymede footprint and main emission show similar variability but are not strongly linked to magnetospheric conditions
- The position of the main emission depends on central meridian longitude, which reflects the importance of magnetospheric local time asymmetries

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

M. F. Vogt,
mvogt@bu.edu

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Variability of Jupiter's Main Auroral Emission and Satellite Footprints Observed With HST During the Galileo Era

Marissa F. Vogt¹ , Matthew Rutala^{1,2} , Bertrand Bonfond³ , John T. Clarke^{1,2} , Luke Moore¹ , and Jonathan D. Nichols⁴ 

¹Center for Space Physics, Boston University, Boston, MA, USA, ²Department of Astronomy, Boston University, Boston, MA, USA, ³Space Sciences, Technologies and Astrophysics Research (STAR) Institute, LPAP, Université de Liège, Liège, Belgium, ⁴Department of Physics and Astronomy, University of Leicester, Leicester, UK

Abstract Hubble Space Telescope images of Jupiter's UV aurora show that the main emission occasionally contracts or expands, shifting toward or away from the magnetic pole by several degrees in response to changes in the solar wind dynamic pressure and Io's volcanic activity. When the auroral footprints of the Galilean satellites move with the main emission this indicates a change in the stretched field line configuration that shifts the ionospheric mapping of a given radial distance at the equator. However, in some cases, the main emission shifts independently from the satellite footprints, indicating that the variability stems from some other part of the corotation enforcement current system that produces Jupiter's main auroral emissions. Here, we analyze HST images from the Galileo era (1996–2003) and compare latitudinal shifts of the Ganymede footprint and the main auroral emission. We focus on images with overlapping Galileo measurements because concurrent measurements are available of the current sheet strength, which indicates the amount of field line stretching and can influence both the main emission and satellite footprints. We show that the Ganymede footprint and main auroral emission typically, but do not always, move together. Additionally, we find that the auroral shifts are only weakly linked to changes in the current sheet strength measured by Galileo. We discuss implications of the observed auroral shifts in terms of the magnetospheric mapping. Finally, we establish how the statistical reference main emission contours vary with central meridian longitude and show that the dependence results from magnetospheric local time asymmetries.

Plain Language Summary Jupiter's main auroral emission is thought to be the result of a current system that develops to help circulate plasma from Io as it moves through Jupiter's magnetosphere. There are many factors that can influence the position and brightness of Jupiter's main emission, including the solar wind and internal factors like Io's volcanic activity. The auroral footprints of Jupiter's moons Io, Europa, and Ganymede can provide important clues to what factors influence variability in the main auroral emission because some processes, like those that affect the radial stretching of the magnetic field, will affect the position of both the satellite footprints and the main emission. In this study, we quantify and compare variability in the position of Jupiter's main auroral emission and the Ganymede footprint in images from the Hubble Space Telescope. We focus on images from the Galileo era (1996–2003) and compare variability in the auroral emissions to Galileo observations of magnetospheric variability. We find that the Ganymede footprint and main auroral emission typically change in the same way, but find the expected relationship between the auroral motion and the magnetic field measured by Galileo to be weak.

1. Introduction

It has been nearly 30 years since the Hubble Space Telescope took its first images of Jupiter's aurora with its Faint Object Camera (Caldwell et al., 1992). Subsequent high-resolution images with HST's Wide Field and Planetary Camera 2, Advanced Camera for Surveys, and Space Telescope Imaging Spectrograph (STIS) instruments have shown that Jupiter's ultraviolet auroral emissions can be classified into three types. From most equatorward to poleward, they are: the equatorward emissions, which include auroral injection signatures and the magnetic footprints of the Galilean satellites Io, Europa, Ganymede, and Callisto; the main auroral emission, a relatively constant and narrow ($\sim 1^\circ$ – 3° latitudinal width) band of emissions forming a kidney bean shape in the northern hemisphere and an oval in the south; and the polar emissions, which are highly variable and include flares, spots, a dark region, and arc-like features.

Jupiter's main auroral emission is thought to be the result of a corotation enforcement current (CEC) system that arises due to the breakdown of plasma corotation in the middle magnetosphere (Cowley & Bunce, 2001; Hill, 2001). The primary source of plasma in Jupiter's magnetosphere is the moon Io, whose volcanic activity adds plasma to the system at a rate of $\sim 500\text{--}1,000$ kg/s (Thomas et al., 2004). As plasma diffuses radially outward from its source at Io's orbit (5.9 Jovian radii or R_J ; $1 R_J = 71,492$ km) its azimuthal velocity decreases to conserve angular momentum, and a CEC system develops. The plasma is accelerated back up toward corotation by a $\mathbf{j} \times \mathbf{B}$ force provided by the radially outward current, and the upward (out of the ionosphere) field-aligned current, carried by downward moving electrons, is thought to produce the main auroral emission. Though the corotation enforcement theory for the production of Jupiter's main aurora has been widely accepted, Bonfond et al. (2020) recently highlighted several pieces of observational evidence that are broadly inconsistent with the typical CEC description. Several recent observations and theoretical studies indicate that waves, including ULF (Lysak & Song, 2020; Pan et al., 2021), EMIC (Yao et al., 2021), Alfvén (Gershman et al., 2019; Saur et al., 2018), and whistler mode waves (Elliott et al., 2018), may play a larger role in the generation of the Jovian aurorae than previously foreseen. Any auroral origin theory must be ultimately able to account for observed auroral properties like brightness, position, and both temporal and spatial variability.

Though sometimes called the “main oval”, Jupiter's main auroral emissions are actually shaped like a kidney bean in the northern hemisphere, as shown in the HST polar projections in Figure 1, due to the presence of a weak-field anomaly in the internal magnetic field (Grodent, Bonfond, et al., 2008). The southern main auroral emissions form an oval roughly centered on the southern magnetic pole, which is tilted by $\sim 10^\circ$ with respect to the rotation axis. The main emission brightness ranges from tens to thousands of kiloRayleighs (kR) and varies temporally as well as with central meridian longitude (CML) and local time (e.g., Grodent et al., 2003). Its morphology also varies with local time: the main emission width ranges from $\sim 0.5^\circ\text{--}1^\circ$ in the dawn to noon sector to as wide as $\sim 3^\circ$ near dusk, and a “discontinuity” typically appears pre-noon (Radioti et al., 2008). The location of the main emission maps roughly to a source region at $\sim 20\text{--}40 R_J$ in the magnetosphere, which is consistent with the CEC theory (e.g., Nichols et al., 2020; Nichols & Cowley, 2004), though the mapping varies with local time (Vogt et al., 2011). The main emission occasionally contracts or expands, shifting toward or away from the magnetic pole, by several degrees (e.g., Grodent, Gérard, Radioti, et al., 2008; Nichols et al., 2009). This motion is often referred to as a “latitudinal shift” and is largely in the direction of magnetic, not jovigraphic, latitude, particularly in the northern hemisphere. This type of variability, which has been linked to both changes in the solar wind dynamic pressure (Grodent et al., 2003) and changes internal to the magnetosphere like volcanic activity on Io or changes in the hot plasma pressure gradient (Bonfond et al., 2012; Nichols, 2011; Nichols et al., 2015), is the focus of our study.

There are two likely explanations for the observed latitudinal shifts of Jupiter's main auroral emission. The first is a change in the magnetic field configuration that shifts the ionospheric mapping of a given radial distance in the equatorial magnetosphere. For example, if a magnetic field line becomes more (less) radially stretched compared to its average state then its ionospheric footprint would shift equatorward (poleward) compared to its typical mapping, as illustrated in Figure 1 (top left). The figure illustrates why the ionospheric footprint of a fixed radial distance in the magnetosphere, such as Ganymede's orbit at $15 R_J$, shifts equatorward as the field becomes increasingly radially stretched. In this illustration, the dashed outer blue field line (weak current sheet) and the solid inner red field line (strong current sheet) both cross the equator at the same radial distance but the ionospheric footprint of the dashed blue field line is poleward of the solid red field line. Additionally, the two solid field lines in the figure have the same ionospheric footprint, but the equatorial crossing point is much larger for the radially stretched red field lines (strong current sheet) than for the more dipolar blue field lines (weak current sheet). Therefore, a change in the magnetic field configuration can lead to a latitudinal shift of the main auroral emission by shifting the ionospheric footprints of field lines that are linked to the radial distance where the CEC system peaks. A change in the magnetic field configuration would also affect the latitudinal positions of the auroral satellite footprints since they are linked to a fixed orbital distance.

The second likely cause of latitudinal shifts in Jupiter's main auroral emission is a change in part of the CEC system that produces the main auroral emission, such as a change in the plasma mass loading rate or in the radial profile of the plasma azimuthal velocity. These changes can alter the radial distance of the peak CECs, as shown in the magnetodisk modeling work of Nichols (2011) and Nichols et al. (2015), and latitudinally shift the main emission as its equatorial radial mapping changes. These changes may also lead to a shift in the satellite footprint

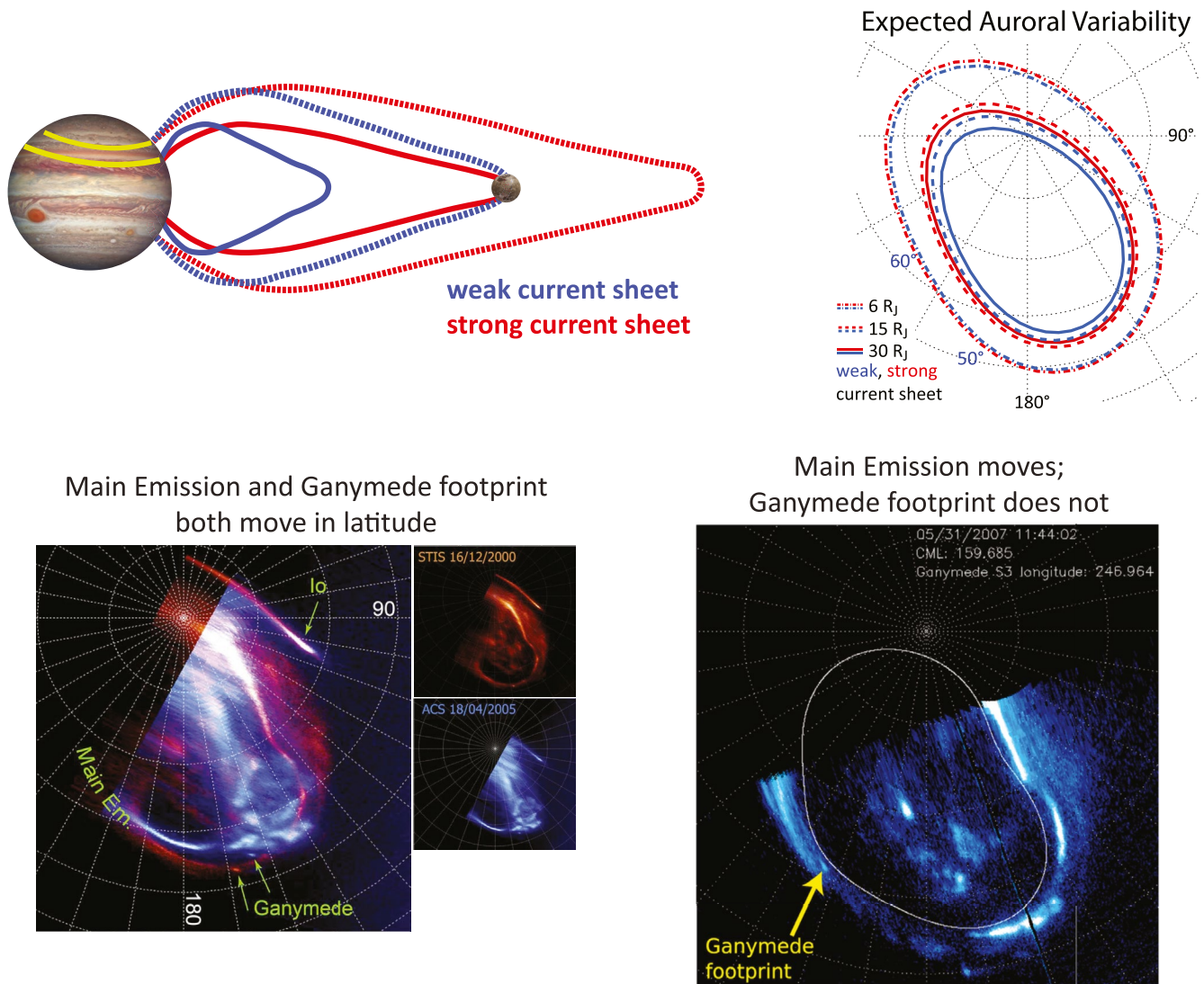


Figure 1. (top left) Illustration showing how a change in the configuration of magnetic field lines in Jupiter's magnetosphere can lead to a latitudinal shift in auroral features like the main emission or the Ganymede footprint (not to scale). The blue (red) field lines show the field configuration for a weak (strong) current sheet. (top right) Results of tracing model field lines to the northern ionosphere from $6 R_J$ (dash-dot), $15 R_J$ (dashed), and $30 R_J$ (solid) in the jovigraphic equator assuming a weak (blue) or strong (red) current sheet consistent with the measured current sheet variability observed by Galileo. Modified from Figure 8 of Vogt et al. (2017). (bottom left) Two HST polar auroral images from 2000 (red) and 2005 (blue) are overlaid, showing how the Ganymede footprint and main auroral emission can shift latitudinally by several degrees. Reproduced from Grodent, Gérard, et al. (2008). (bottom right) HST polar image of Jupiter's aurora from Bonfond et al. (2012) in which the main auroral emission is extremely expanded while the Ganymede footprint is slightly equatorward of its reference position. The white line shows the Bonfond et al. (2012) reference main emission.

locations, as the Nichols modeling work shows. However, in general, changes in the CEC system would not necessarily lead to a shift in the satellite footprint locations unless the field geometry also changed. For example, the Ganymede footprint is located slightly equatorward of its expected location in the auroral image reproduced in Figure 1 (bottom right), but the main auroral emission is extremely expanded (Bonfond et al., 2012). The latitudinal motion of the satellite footprints is therefore a useful diagnostic tool for identifying the cause of latitudinal shifts in the main auroral emission.

In this article, we survey the HST auroral images from the Galileo era (1996–2003) and compare how latitudinal shifts of the Ganymede footprint compare to concurrent shifts in the main auroral emission, with the ultimate goal of furthering our understanding of how Jupiter's magnetosphere-ionosphere (M-I) coupling system varies in time. We focus on images with overlapping Galileo measurements because concurrent information is available about

the amount of field line radial stretching, which can affect the position of both the main emission and satellite footprints (Vogt et al., 2017). We consider whether the main emission and satellite footprints occur independently and compare the auroral shifts to Galileo fits of the current sheet current density. Section 2 presents an overview of the data used in this study, Section 3 describes how we identified the position of the main auroral emission and corrected for viewing geometry, and Section 4 discusses our results and future work. We conclude in Section 5 with a summary.

2. Data Used in This Study

2.1. HST Data Availability, Image Reduction, and Limb Fitting

In this study, we use images taken with HST's STIS instrument, which has a resolution of 0.0246 arcsec/pixel. We are interested in comparing auroral variability to changes measured in Jupiter's magnetosphere by the Galileo spacecraft, which orbited Jupiter from 1996 to 2003. Therefore, we began our analysis by looking at the 170 images that are available from 25 unique dates beginning in September 1996 and ending in February 2001. These images come from observing programs 7308, 7769, 8171, and 8657. Most of the images have been analyzed in some way in previous studies (e.g., Clarke et al., 2002; Grodent et al., 2003) but with a different focus than our present work. An additional 13 images are available from observing program 9685 during February 24–26, 2003 (DOY 55–57), though the last Galileo magnetometer data available from Jupiter's magnetosphere are from November 2002, so we have excluded these from our study.

From the initial list of 170 images, we have excluded 27 images (13 from the northern hemisphere and 14 from the southern hemisphere) in which our analysis was unable to clearly identify a significant part of the main emission (see Section 3), almost always because of an unfavorable viewing geometry. Though the main emission is not circular, especially in the northern hemisphere, it is still roughly centered on the magnetic pole in both hemispheres. Jupiter's $\sim 10^\circ$ dipole tilt, toward $\sim 200^\circ$ System III (SIII) longitude (left handed), means that the visibility of the main emission is heavily biased for certain CMLs. The 82 northern hemisphere images used in this study have CMLs ranging from $\sim 90^\circ$ to $\sim 290^\circ$ with a median of $\sim 180^\circ$, and the 61 southern hemisphere images used in this study have CMLs ranges of $\sim 300^\circ$ – 360° and $\sim 0^\circ$ – 120° . Table S1 in Supporting Information S1 lists the date, time, CML, and other relevant details for the 143 images used in this study.

HST images were reduced following the latest version of the BU pipeline process (see Clarke et al., 2009). This process 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. The planetary limb fitting provides an uncertainty of up to a few pixels in the position of different auroral features. In order to mitigate the effects of this uncertainty on our analysis we consider the relative positions of the main auroral emission and Ganymede footprint in addition to the precise position or shift with respect to a fixed reference contour. In our image reduction, we used the same planetary center pixel values as Bonfond et al. (2017) and confirmed that the satellite footprint locations we obtained matched the coordinates provided in their Supporting Information. The Ganymede or Europa footprints were detected in roughly half of the 143 images used in this study: 62 images contained the Ganymede footprint (34 in the northern hemisphere and 28 in the southern hemisphere) and 7 images included the Europa footprint in the southern hemisphere. In our analysis, we focus on the Ganymede footprints because there are so few images containing the Europa footprint and exclude three images (one from the northern hemisphere and two in the southern hemisphere) in which the Ganymede footprint is located very close to the limb of the planet, which makes it difficult to accurately characterize any shift of the footprint with respect to the reference footpath or the main emission.

2.2. Galileo Data Used in This Study

The Galileo spacecraft completed over 30 orbits of Jupiter, surveying the magnetosphere at radial distances from $3.6 R_J$ to $\sim 150 R_J$ and providing excellent coverage at nightside local times, as shown by the black orbit tracks in Figure 2. Colored boxes in Figure 2 show the spacecraft position at the times of all images used in this study excepting the two images from May 28, 1998 (DOY 148), when Galileo was located in the predawn middle magnetosphere but no concurrent magnetometer data are available. Galileo was located inside of $30 R_J$ for 32 of our 143 HST images, in the middle to outer magnetosphere for 76 images, and in the solar wind or magnetosheath

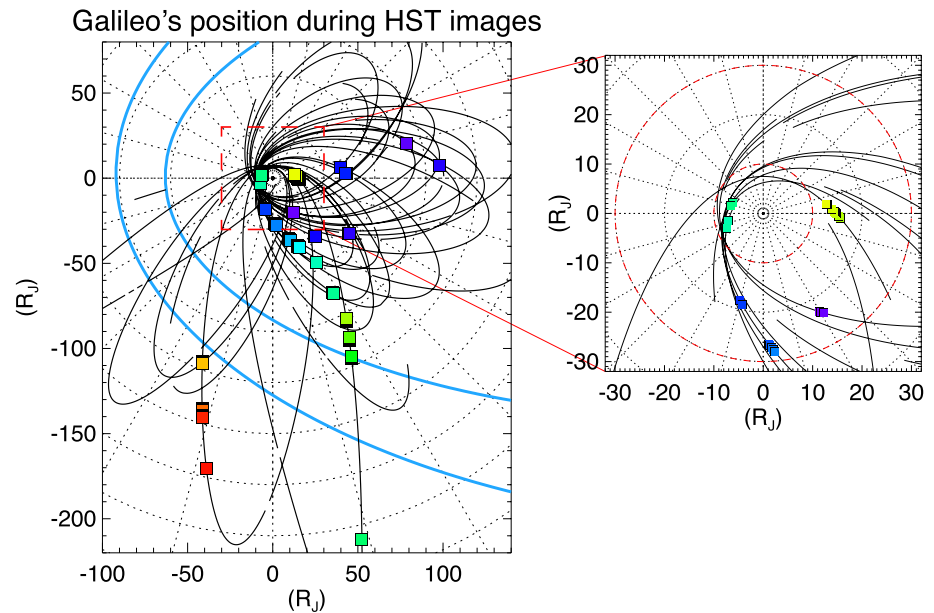


Figure 2. (left) Black lines show the orbital path of the Galileo spacecraft projected onto the equatorial plane, with the sun to the left. Lines are drawn only at times with available magnetic field measurements. Colored boxes show Galileo's position at the times of the 143 HST images used in this study, with the exception of the two HST images from May 28, 1998 (DOY 148), when no magnetometer data are available. Light blue lines show the positions of the expanded and compressed Joy et al. (2002) magnetopause. (right) Galileo's orbital path projected onto the equatorial plane (black lines) along with its position at the times of HST images (colored squares) in the inner and middle magnetosphere. Galileo's trajectory is shown only for the 10 orbits for which HST images overlap or nearly overlap with intervals when the current sheet best fit $\mu_0 I_0$ was calculated (when the spacecraft was located between 10 and 30 R_J —see the red dashed circles).

for the remaining 35 images. For all images when Galileo was located in the solar wind or magnetosheath the spacecraft was located outside of the expanded Joy et al. (2002) magnetopause (outer light blue line in Figure 2).

Images from intervals when the spacecraft was located inside of 30 R_J are particularly relevant because real-time information is available about Jupiter's current sheet and the degree of radial stretching in the magnetic field. Vogt et al. (2017) analyzed temporal variability in magnetometer data from radial distances 10–30 R_J in each of Galileo's orbits. Specifically, they obtained an orbit-by-orbit fit of the Connerney et al. (1981) current sheet model parameter $\mu_0 I_0$, the current sheet current density, which indicates the strength of the current sheet or the amount of radial field stretching. Larger values of $\mu_0 I_0$ indicate a stronger current sheet and a more radially stretched field. The best fit $\mu_0 I_0$ values are shown in the top panel of Figure 3; we note that because the focus of Figure 3 is a comparison to the HST auroral images the time range of Figure 3 omits some Galileo $\mu_0 I_0$ fits from 1996 to early 1997 and from late 2001 to 2002. Error bars indicate variability in the inbound and outbound $\mu_0 I_0$ fits of each orbit, though the $\mu_0 I_0$ fit values were generally stable on the ~ 5 –10 days timescale during which the spacecraft was located at distances from 10 to 30 R_J . Auroral mapping models show that the overall $\mu_0 I_0$ variability would be expected to produce a $\sim 2.3^\circ$ shift in the ionospheric position of model field lines traced from 30 R_J , a $\sim 1.5^\circ$ shift in the modeled Ganymede footprint location, and a $\sim 0.7^\circ$ shift in the modeled Io footprint location. The top right of Figure 1 shows an example of the expected auroral shifts in the northern ionosphere that would be consistent with the measured current sheet variability observed by Galileo, estimated by tracing model field lines with different current sheet parameters. Vogt et al. (2017) performed an initial analysis of 27 HST images with similar CMLs to examine how the size of the main “oval” changed with the contemporaneous best fit $\mu_0 I_0$, but did not find a clear relationship. Here, we expand on that initial work on the main emission and also consider how the best fit $\mu_0 I_0$ affects the observed locations of the satellite footprints.

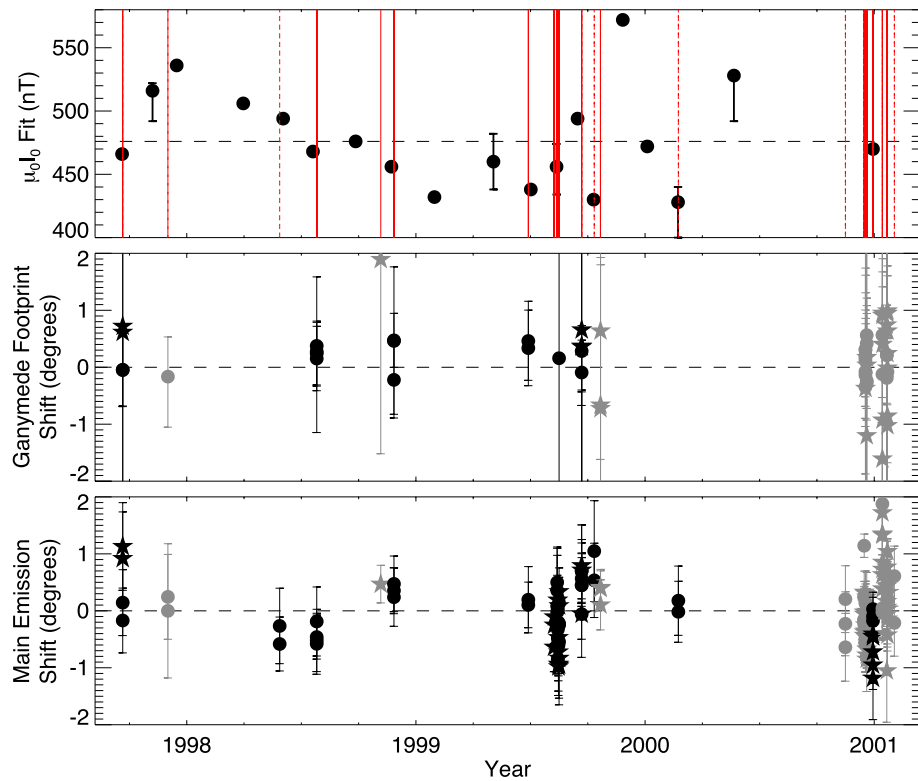


Figure 3. Time series of the current sheet current density, $\mu_0 I_0$, and auroral shifts during the Galileo era. (top) Best fit $\mu_0 I_0$ calculated using Galileo data as a function of time. Error bars show the variability obtained by fitting the inbound and outbound portions of each Galileo orbit separately (see text). Red lines show times of the HST images used in this study with (solid) and without (dashed) a visible Ganymede footprint. The dashed horizontal line at 476 nT indicates the average $\mu_0 I_0$ fit from all Galileo orbits. (middle) Ganymede footprint shift (see text) as a function of time. In this and the next panel data from northern hemisphere images are plotted as circles and data from southern hemisphere images are plotted as star symbols; gray symbols indicate data from auroral images with no corresponding $\mu_0 I_0$ fit. Both the Ganymede footprint and main emission shifts are defined as positive if the relevant auroral feature is poleward of the reference contour/footpath and negative if it is equatorward. Error bars indicate the uncertainty in the Ganymede footprint position reported by Bonfond et al. (2017; see text). (bottom) Mean main auroral emission shift in each image, corrected for central meridian longitude (CML dependence); see text), as a function of time. Error bars indicate the standard deviation of the main emission shift.

3. Analysis: Main Emission Identification and CML Correction

Since Bonfond et al. (2017) have already identified the satellite footprint locations in our images, after confirming these locations the primary task in our analysis was to obtain the position of the main auroral emission. Figure 4 illustrates our approach using a northern hemisphere image from November 25, 1998 at a CML of 164.2°. We began by identifying “slices” of magnetic longitude, assuming the magnetic pole is located at 10.31° latitude and 196.61° System III longitude (left handed) following the JRM09 field model (Connerney et al., 2018), with a resolution of 2° longitude. The thick colored lines emanating from the magnetic pole in the left panel of Figure 4 show some of these magnetic longitude slices, drawn every 10° in magnetic longitude.

Next, we identified the position where each magnetic longitude slice intersects with the Nichols et al. (2009) reference main emission, drawn in gray in Figure 4. We then obtained a Gaussian fit to the auroral brightness along each magnetic longitude slice within the region that is $\pm 4.5^\circ$ magnetic latitude from the reference main emission, outlined by the two pink contours in the left panel of Figure 4. The right panel of Figure 4 shows auroral brightness and Gaussian fits from selected magnetic longitude slices as a function of distance from the Nichols et al. (2009) reference contour, defined as positive for points poleward of the reference contour. The color of each line corresponds to the color of the magnetic longitude slice drawn in the left panel of Figure 4; for clarity, we have only drawn lines every 15° of magnetic longitude. Finally, we identified the main emission location, plotted as white stars in Figure 4, as the position of the peak in the Gaussian fit on each magnetic longitude slice. We

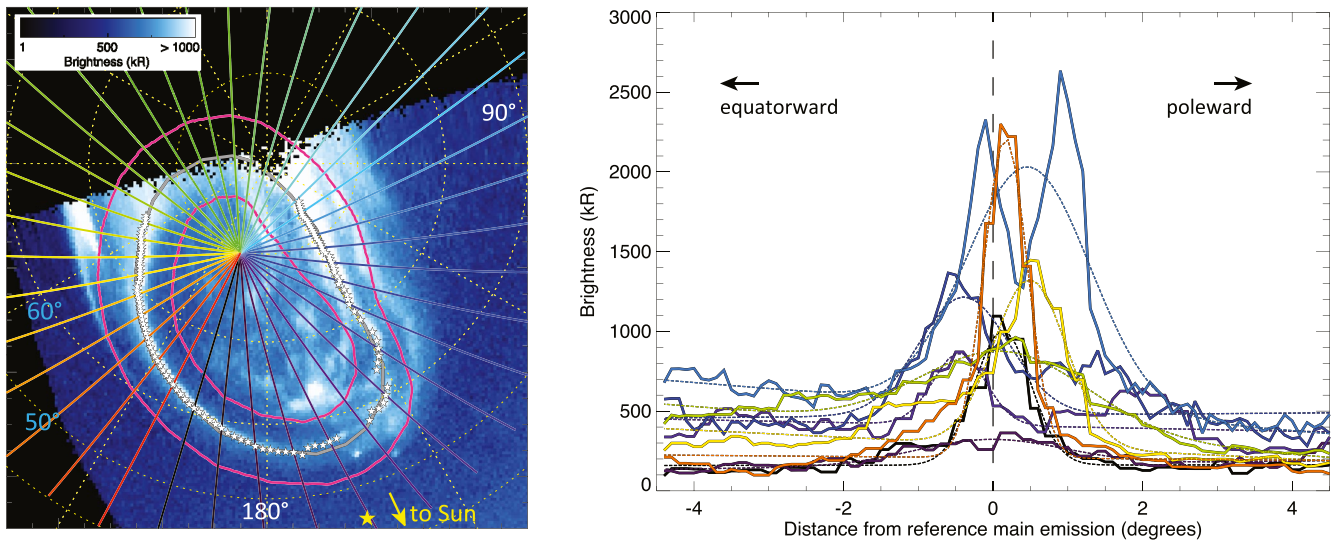


Figure 4. (left) Polar projection of an HST image taken on November 25, 1998 with CML 164.2° (yellow star). Colored lines radiating outward from the magnetic pole show the magnetic longitude “slices” along which we fit the auroral brightness with a Gaussian in the region between the two pink contours. The gray line shows the reference main emission contour of Nichols et al. (2009). White stars show the identified main emission locations for this image, with a spacing of 2° magnetic longitude. System III left-handed longitude is noted in white text and latitude is noted in blue. (b) Auroral brightness (thick solid lines) and Gaussian fits (thin dashed lines) along selected magnetic longitude “slices” from the left panel of Figure 4, plotted as a function of distance from the Nichols et al. (2009) reference contour in degrees of magnetic latitude. Each brightness profile has been plotted in the same color of the corresponding magnetic longitude slice.

have confirmed that we obtain very similar main emission positions whether we use a Gaussian fit approach or whether we define the main emission location as the point of peak brightness along each magnetic longitude slice. The difference between the main emission points identified with the two different approaches was typically $\sim 0.1^\circ$ in spherical distance. Both approaches lead to very similar estimates of auroral variability and overall conclusions as described in Section 4.

In our analysis, we treat the main emission as a distinct point at each longitude rather than as a broad feature. This approach makes it easy to calculate the main emission shift with respect to a reference contour and also allows us to easily identify the main emission in each image via the same algorithm. However, it is undoubtedly an oversimplification, particularly for the dusk emissions that are not typically well-defined or may feature multiple arcs.

In our analysis, we exclude points where the main emission was misidentified (for example, because of a feature like the Ganymede footprint) or is sharply discontinuous. Therefore, there are some gaps in the main emission location stars shown in Figure 4. Many of these gaps occur in the auroral discontinuity region at pre-noon local times (Radioti et al., 2008) and in the northern auroral “kink” sector, where the main emission can be difficult to identify and often features multiple arcs. As previously mentioned, we discarded completely 26 images for which we were unable to obtain good fits to the main auroral emission, largely due to the viewing geometry.

Several previous authors have identified reference main emission contours by co-adding images (Bonfond et al., 2017; Grodent et al., 2003; Nichols et al., 2009). We take a slightly different approach here, defining a statistical reference main emission contour by identifying the average position of the main emission. For example, Figure 5 shows the distribution of the main emission positions along each magnetic longitude slice identified using the approach described above. Each box in Figure 5 has dimensions of 2° magnetic longitude by 0.1° magnetic latitude and its color indicates the number of images in which the main emission position, as identified by the peak of the Gaussian fit, was located within that box. The main emission locations are scattered by as much as $\sim 3^\circ\text{--}4^\circ$ in magnetic latitude but are concentrated in narrow bands that are close to the Nichols et al. (2009) reference contour in the north and the Grodent et al. (2003) reference contour in the south (thick gray lines). The scatter in the main emission peak locations is generally largest near dusk and smallest near dawn, where the main emission tends to be narrow and well-defined in HST images. We define our reference contour by calculating the average magnetic latitude of the main emission in each magnetic longitude bin. Our resulting reference contours for the northern and southern hemispheres are shown by the thick black

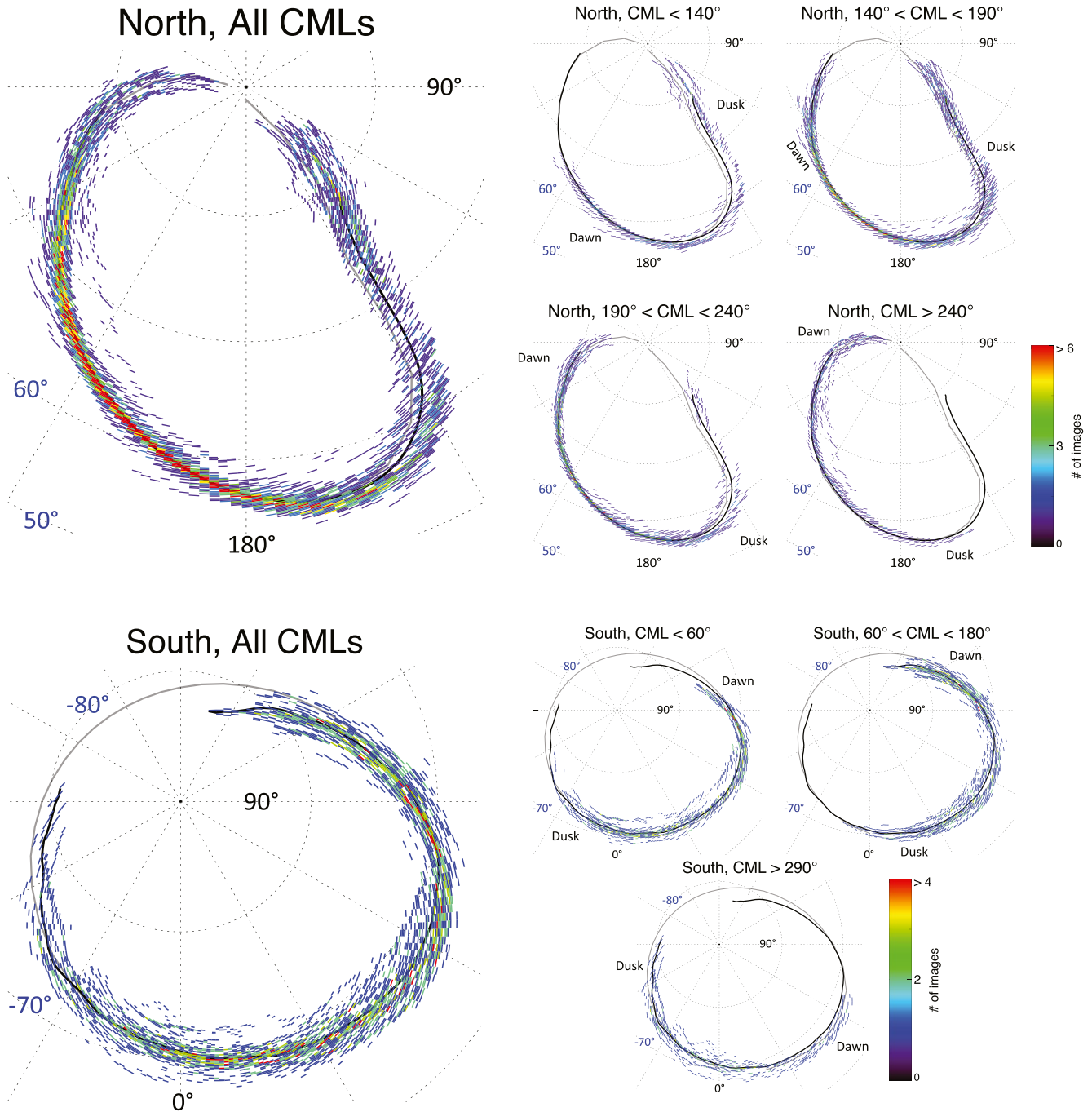


Figure 5. Distribution of the main emission locations identified following the approach described in Section 3, shown here in a polar view looking down on the planet in the northern hemisphere and looking up at the planet in the southern hemisphere. Colors represent the number of images for which the main emission is located in each 2° magnetic longitude by 0.1° magnetic longitude box. Data are plotted separately for all images (left column) and for images from the specified CML ranges. Thick gray contours in all panels show the reference contours of Nichols et al. (2009) in the northern hemisphere and Grodent et al. (2003) in the southern hemisphere. Thick black lines show the statistical main emission reference contour defined in this study using images from all CMLs.

lines in Figure 5. Figure 6 shows that our statistical reference contours are similar in shape and location to the reference contours derived by Bonfond et al. (2017), Grodent et al. (2003), and Nichols et al. (2009). Our statistical reference contour most closely matches Grodent et al. (2003), as expected since that study and ours used a nearly identical set of images.

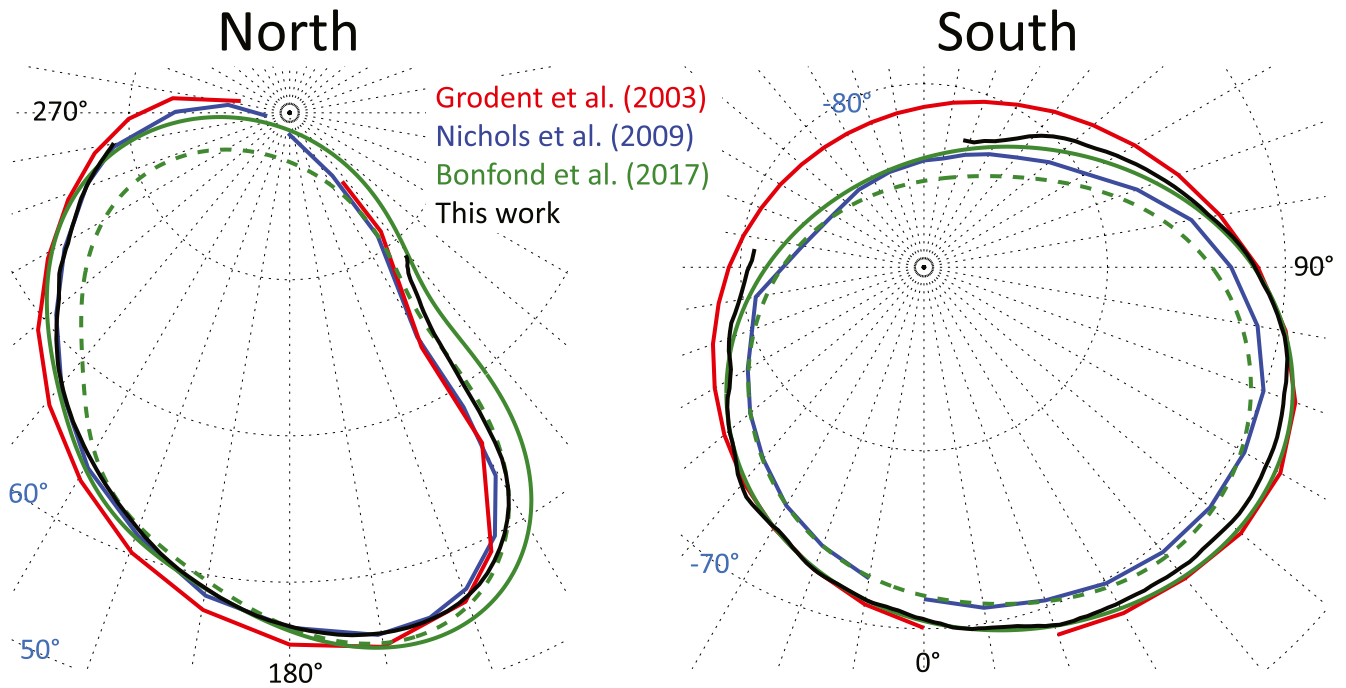


Figure 6. Polar plots comparing the location of our statistical reference main emission contour (black) to the locations of the previous reference contours identified by Bonfond et al. (2017; green dashed and solid lines for the contracted and expanded reference contours, respectively), Grodent et al. (2003; red), and Nichols et al. (2009; blue). The left panel shows the reference contours for the northern hemisphere and the right panel shows the reference contours for the southern hemisphere.

The main emission position varies with CML (Grodent et al., 2003), so we have also plotted the distribution of main emission positions separately for certain CML ranges in Figure 5 and we have calculated CML-specific statistical reference main emission contours, which are plotted in the top panel of Figure 7. In the northern hemisphere, we considered the following CML ranges: CMLs 80°–140° (purple), 140°–190° (blue), 190°–240° (green), 240°–290° (red); in the southern hemisphere, we considered CMLs 0°–60° (purple), 60°–180° (blue), and 290°–360° (red). (Note that there are no northern images with CMLs less than 80° or larger than 290°, and no southern hemisphere images with CMLs between 180° and 290°.) In the northern hemisphere, the main emission is most expanded at small CMLs (purple) and becomes more contracted with increasing CML (e.g., red contour), as noted by Grodent et al. (2003). The CML dependence is not as noticeable in the southern hemisphere as it is in the northern hemisphere, though again the reference contour at the earliest CMLs (red) is most expanded. This behavior in both hemispheres is consistent with the main emission shifting poleward at dusk compared to its average location for a given location, as we discuss in more detail in Section 4.3.

4. Results and Discussion

4.1. Comparison of Main Emission and Satellite Footprint Shifts

After identifying the main emission in each HST image we can now consider whether the main emission and satellite footprints shift independently or whether they demonstrate similar temporal behavior (i.e., whether poleward motion of the main emission is typically accompanied by poleward motion of the satellite footprints). For each image that contained a satellite footprint we define the Ganymede footprint shift as the minimum spherical distance between the observed satellite footprint and the reference footpath derived by Bonfond et al. (2017). Similarly, we define the main emission shift as the mean distance between the main emission and the CML-specific statistical reference contour (see Section 3). For both the main emission and Ganymede footprint we define the shift as positive if the relevant auroral feature is poleward of the reference contour/footpath and negative if it is equatorward.

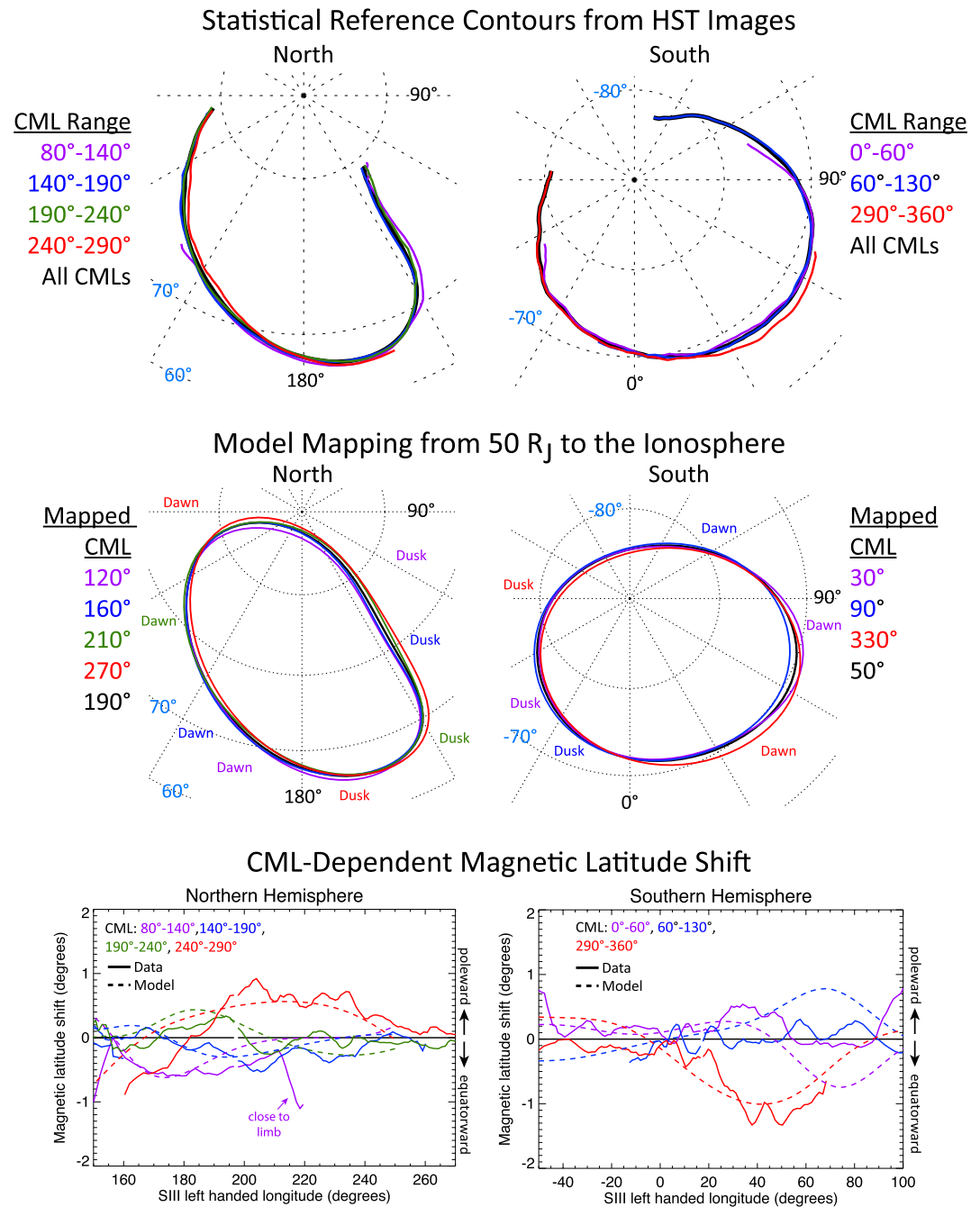


Figure 7. (top) Polar projections of the statistical reference contours derived for various CML bins. In the northern hemisphere the CML bins are 80°–140° (purple), 140°–190° (blue), 190°–240° (green), and 240°–290° (red), and in the southern hemisphere the CML ranges are 0°–60° (purple), 60°–130° (blue), and 290°–360° (red). Our statistical reference emissions for all images (from all CMLs) are plotted in black. (middle) Ionospheric contours mapping to 50 R_j in the magnetosphere using the Vogt et al. (2011) flux mapping model with JRM09 as the internal field model, calculated for CML 120° (purple), 160° (blue), 210° (green), and 270° (red) in the northern hemisphere, and 30° (purple), 90° (blue), and 330° (red) in the southern hemisphere. Black contours show the ionospheric mapping for CML 190° in the northern and 50° in the southern hemisphere. (bottom) Magnetic latitudinal shift between the CML-specific reference contour and the average statistical main emission contour plotted as a function of SIII left handed longitude. Solid lines show the observed latitudinal shift and dashed lines show the latitudinal shift predicted from the mapping model.

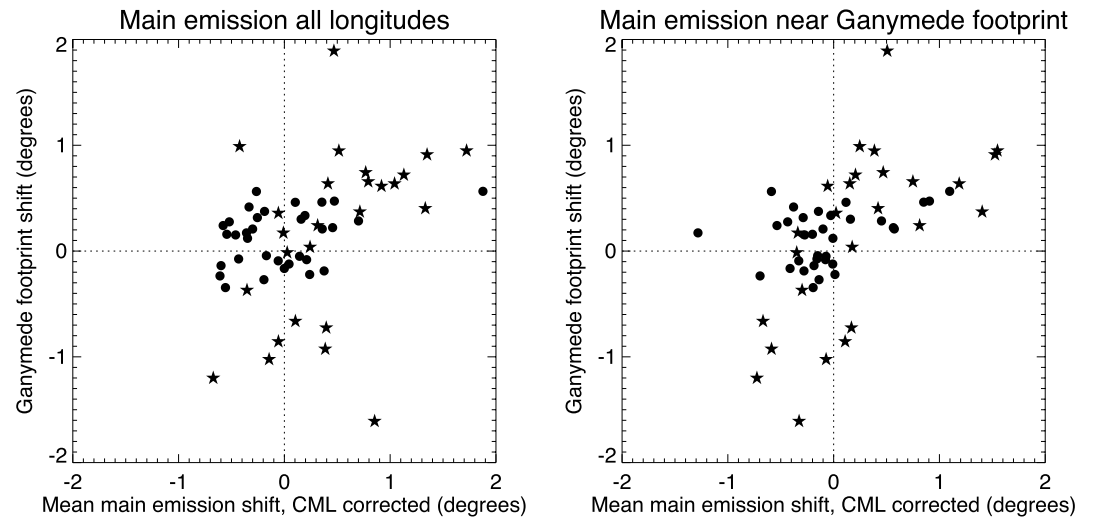


Figure 8. Plots of the Ganymede footprint shift and main auroral emission shift. The auroral shifts are calculated as the mean spherical distance between the respective auroral feature (footprint or main emission) and a specific reference contour (see text) and are defined as positive for a poleward shift. In the left panel, the main auroral emission shift is calculated using the main emission position at all longitudes and in the right panel, the main auroral emission shift is calculated using only longitudes near the Ganymede footprint (see text). Circles and stars indicate northern and southern hemisphere images respectively.

Figure 8 shows plots of the Ganymede footprint shift and the main emission shift. This figure contains data from the 59 images (33 of the northern hemisphere and 26 of the southern hemisphere) for which the main auroral emission was clearly identified and the Ganymede footprint was not located close to the limb of the planet (see Section 2.1). In the left panel, we calculated the main emission shift using the main emission location at all longitudes; in the right panel, we calculated the main emission shift using only the main emission points in the 10° magnetic longitude bin (e.g., 0° – 10° , 10° – 20° , etc.) closest to the Ganymede footprint. In both plots, two thirds of the points are located in the upper right or lower left quadrants, indicating that the footprint and main emission shift together (both poleward or both equatorward). The linear correlation coefficient of the two shifts is stronger when considering the main emission shift only at magnetic longitudes near the Ganymede footprint (linear correlation coefficient 0.52) instead of at all longitudes (linear correlation coefficient 0.37). This could indicate that the processes that change the magnetic field configuration and produce auroral shifts are somewhat localized.

Of the images for which the Ganymede footprint and main emission shift separately, most come from the northern hemisphere and involve an equatorward motion of the main emission. Interestingly, in all four images from July 26, 1998 (DOY 207) the main emission was shifted equatorward while the Ganymede footprint was shifted poleward (all four images from this date are of the northern hemisphere). The images which feature opposite footprint and main emission shifts do not otherwise appear to be more likely to occur under specific conditions or circumstances like date, CML, footprint longitude, best fit magnetodisk parameter $\mu_0 I_0$, etc.

Overall, we conclude that the main emission and Ganymede footprint generally, but do not always, shift together. However, our conclusion comes with several caveats about the uncertainty of the planetary limb fitting/center pixel finding process, which affects the absolute shifts of both the main emission and Ganymede footprint. Due to the uncertainty in fitting the planet center in each HST image, Bonfond et al. (2017) assumed an uncertainty of 8 pixels, which typically corresponds to $\sim 2^\circ$ spherical distance, in the footprint spot locations from STIS images. This uncertainty is larger than the typical auroral shifts we have calculated here but is likely an overestimate (a more typical assumed uncertainty value is ~ 3 pixels). We can remain reasonably confident in our analysis since the uncertainty associated with the limb fitting applies to both the main emission and the Ganymede footprint. However, exactly whether an n -pixel error in the planetary center finding shifts both the main emission and footprint poleward/equatorward together or shifts them in opposite directions depends on factors like the image CML, position of the auroral feature, and direction of the limb fitting error. Using a subset of representative images at a range of CMLs we calculated that a 3 pixels uncertainty in the planetary center pixel results in a typical

variability in the main emission position of $\sim 0.2^\circ$ – 0.8° , with an average value of $\sim 0.4^\circ$. We note that the time series in Figure 3 shows that the main emission shifts among images from the same day can vary significantly, sometimes even being of opposite sign. We do not believe this is indicative of a physical process—the timescale is likely too short—but probably reflects some of the error and uncertainty in our analysis, including the planet center pixel finding and main emission identification. Finally, it is important to note that the Ganymede footprint which provides the basis for calculating the footprint shift was derived by Bonfond et al. (2017) using more images, and likely covering a wider range of magnetospheric conditions, than we have considered in our study. Their data set encompassed dates from 1997 to 2014 and included more than 700 images in the north and more than 200 images in the south.

4.2. Auroral Shifts and Magnetodisk Variability

Next, we consider whether the observed Ganymede footprint and main auroral emission shifts display any dependence on the magnetospheric field configuration as indicated by the best fit magnetodisk parameter $\mu_0 I_0$ calculated by Vogt et al. (2017). The best fit $\mu_0 I_0$ values were calculated using Galileo magnetometer data during intervals when the spacecraft was located at radial distances between 10 and 30 R_J in each orbit. Roughly half (68 of 143) of the 143 images used in this study overlapped with or occurred within 2 days of these intervals. Those images come from 10 of the 31 Galileo orbits (C10, E15, E16, E18, C21, C22, C23, I24, I27, and G29) which featured slightly smaller-than-average best fit $\mu_0 I_0$ values. The 68 images with simultaneous/near-simultaneous current sheet measurements include 19 images with a clearly identified Ganymede footprint. The best fit $\mu_0 I_0$ values at the times of our HST images range from 428 to 494 nT, with a mean of 463 nT. By comparison, the best fit $\mu_0 I_0$ values from the full Galileo data set range from 406 to 572 nT, with a mean of 476 nT (see Vogt et al., 2017, Table 1).

Figure 9 shows plots of the main emission shift, Ganymede footprint shift, and the difference between the Ganymede footprint shift and main emission shift as functions of the best fit $\mu_0 I_0$ values corresponding to the dates of each image. In Figure 9a and in the middle panel of Figure 3, the error bars plotted for the Ganymede footprint shift indicate the possible range of shift values due to the 8 pixels uncertainty in the footprint latitude and longitude assumed by Bonfond et al. (2017). In Figure 9b and in the bottom panel of Figure 3, the error bars indicate the standard deviation of the distance between the observed main emission points and the CML-specific reference contour.

We have not calculated correlation coefficients for the quantities plotted in Figure 9 because we believe it is more appropriate to take a more qualitative approach that focuses on general trends. This is in part because the magnitude of the expected auroral shift produced by a given change in the $\mu_0 I_0$ value would depend on many factors, including the ionospheric longitude and radial mapping, CML, and the initial $\mu_0 I_0$ value (this point is illustrated in the top left of Figure 1 and in Figure 11). Similarly, though we have quoted linear correlation coefficients for the Ganymede and main emission shifts plotted in Figure 8, we believe it is more appropriate to take a more qualitative approach generally, focusing on whether the two auroral features shift in the same direction or not. Therefore, here we consider whether the observed auroral shifts are broadly consistent with the $\mu_0 I_0$ fit values.

By our definition, a positive auroral shift means a shift poleward of the statistical main emission or satellite footprint reference contour, which would be consistent with a small current sheet current density $\mu_0 I_0$ or a mostly dipole-like field geometry (see Figure 1), while a negative or equatorward shift would be consistent with a larger $\mu_0 I_0$ and more radially stretched field configuration (see Figure 1). Therefore, we expect a negative correlation between the current sheet $\mu_0 I_0$ fit and the two auroral shifts plotted in Figures 9a and 9b. The main emission shift plotted in Figure 9b is very scattered but there is a very weak anti-correlative trend, with the smallest $\mu_0 I_0$ values featuring only positive shifts. However, the Ganymede footprint shifts plotted in Figure 9a are nearly all positive and they appear to vary independently of the $\mu_0 I_0$ fit values.

The difference between the Ganymede footprint shift and the main emission shift is plotted in Figure 9c. This shift difference is a useful quantity to consider because it provides information about whether the Ganymede footprint and main emission grow closer together or farther apart compared to the distance between their reference contours. We plot the shift difference rather than the distance between the Ganymede footprint and the main emission because the latter quantity depends on several factors, like the satellite longitude and CML, in addition to the current sheet $\mu_0 I_0$ term, so identifying its $\mu_0 I_0$ dependence from observations is not straightforward. The

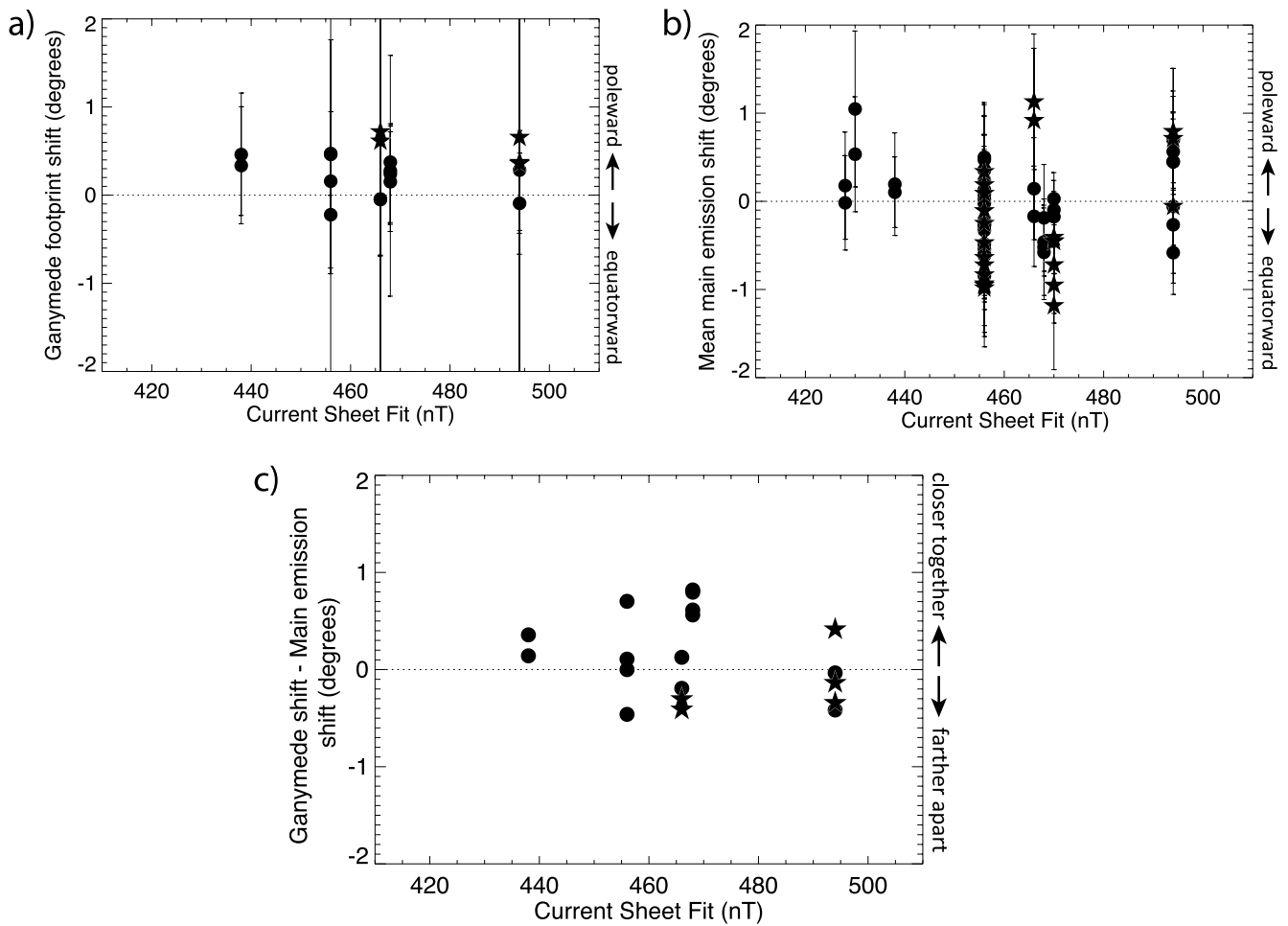


Figure 9. Dependence of the observed auroral shifts on the best fit current sheet current density term $\mu_0 I_0$, obtained from Galileo data, for the date of each HST image. In all panels, circles and stars indicate northern and southern hemisphere images respectively. (a) The Ganymede footprint shift as a function of the best fit $\mu_0 I_0$ for each HST image. Error bars indicate the uncertainty in the Ganymede footprint position reported by Bonfond et al. (2017; see text). (b) As in Figure 9a but for the CML-corrected main auroral emission shift. Error bars indicate the standard deviation of the main emission shift. (c) The difference between the Ganymede footprint shift and the main emission shift as a function of the best fit $\mu_0 I_0$ for each image.

shift difference plotted in Figure 9c will be zero if both the Ganymede footprint and the main emission move latitudinally by the same distance and in the same direction. The shift difference will be positive if the Ganymede footprint and main emission get closer together (if the Ganymede footprint shifts more poleward than the main emission does, or if the Ganymede footprint shifts less equatorward than the main emission does) and will be negative if the footprint and main emission get farther apart. We expect the distance between contours that map to two fixed positions in the magnetosphere (i.e., $15 R_J$ and $30 R_J$) to decrease with increasing radial field stretching or current sheet $\mu_0 I_0$ term (see Figure 1 top right). Therefore, if the radial mapping of the main auroral emission is constant in time then we expect the shift difference plotted in Figure 9c to be positively correlated with $\mu_0 I_0$. However, as was the case for the main emission shift plotted in Figure 9b, the shift difference plotted in Figure 9c shows some scatter but overall shows a very weak anti-correlation with $\mu_0 I_0$, with most negative values occurring at large $\mu_0 I_0$.

Finally, time series of the Ganymede footprint and main auroral emission shifts are plotted in the bottom two panels of Figure 3 for comparison to the best fit $\mu_0 I_0$ time series in the top panel. Galileo measurements of the best fit $\mu_0 I_0$, magnetospheric electron density, and Io dust emission rate, and ground-based observations of the Io plasma torus intensity all show a long-term decrease from roughly 1997 to 2000 (Krüger et al., 2003; Nozawa et al., 2004, 2005). Unfortunately, the HST observations are too sporadic during that interval, and too variable overall, to identify any corresponding long-term trend in the auroral shifts.

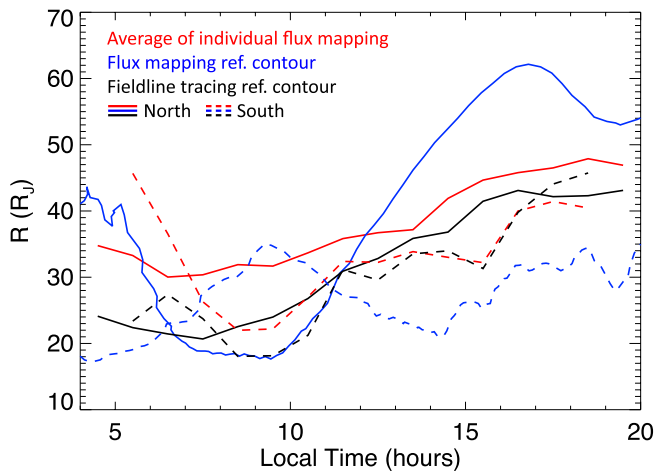


Figure 10. The equatorial mapping of Jupiter's main auroral emission, shown here by the mapped radial distance plotted as a function of the mapped local time. Red lines show the result of averaging the flux mapping of each individual main emission contour from all images in this study, plotted separately for the north (solid) and south (dashed). Blue lines show the flux mapping results for the north (solid) and south (dashed) statistical reference contours, calculated using the average CML value of the images from each respective hemisphere (190° for the north and 50° for the south). Black lines show the average of the individual mappings for each image obtained by tracing field lines using the JRM09 + CAN2020 model (Connerney et al., 2018, 2020) for the north (solid) and south (dashed).

4.3. Main Emission Mapping: CML and Temporal Variability

We now turn to the question of how the main emission's equatorial mapping changes in time. We begin by identifying the average main emission mapping then proceed to compare the observed CML dependence of the average main emission location identified in Section 3 (Figure 5) to the variability over a Jovian rotation period predicted from a mapping model. This analysis is useful to assess whether the observed CML dependence is indicative of a real spatial (CML) variability or whether it reflects temporal changes or other biases. We then consider the observed main emission latitudinal shifts in the context of the measured current sheet current density changes and discuss implications for the M-I coupling system.

For our mapping, we primarily use the flux equivalence approach of Vogt et al. (2011), which is more reliable than tracing field lines from most global models in the middle and outer magnetosphere because it incorporates an empirical model of the magnetic field in those regions and accounts for local time asymmetries. This mapping approach is based on the assumption that the magnetic flux through a region in the ionosphere must equal the flux through the region to which it maps in the equatorial magnetosphere. The model uses a 2-D (radial distance and local time) empirical fit to magnetometer data to calculate the flux threading the equator and a model of Jupiter's internal magnetic field to calculate the flux through the ionosphere. Full details are available in Vogt et al. (2011). We note that the mapping results presented here use the Juno-era JRM09 magnetic field model (Connerney et al., 2018) as the internal field model in the flux mapping. The choice of internal field model can have a significant quantitative effect on the M-I mapping of a specific point (Vogt et al., 2015), but we have confirmed that our choice of

internal field model does not significantly change the qualitative findings presented here. Finally, we note that the mapping model depends on CML but does not include any other temporal variability (i.e., on time scales longer than one Jovian day).

Figure 10 shows the main auroral emission mapping to the jovigraphic equator as a function of the mapped local time. The mapping shows some dependence on hemisphere and whether one employs the flux mapping (red and blue lines) or fieldline tracing (black lines) approach but overall, the main emission typically maps to $\sim 20\text{--}40 R_J$. The red lines show the average mapped location obtained by averaging the individual flux mapping results from each HST image, and the blue lines show the flux mapping result of the statistical reference contour. If the main emission is linked to processes occurring in the equatorial magnetosphere, like corotation breakdown in the CEC theory, we would expect very close agreement between the northern (solid lines) and southern (dashed lines) radial distance mapping. There is a north-south difference in the mapping in Figure 10, but the mapping shows a systematic local time trend for both hemispheres. With the exception of the southern hemisphere reference contour flux mapping (blue dashed line), all mapping approaches suggest that the main emission maps to larger distances near dusk than near dawn by about $10\text{--}15 R_J$. Therefore, we suggest that the north-south mapping discrepancy could be due to systematic biases in the data used to create the northern or southern reference contours or could indicate the uncertainty in the mapping.

The Vogt et al. (2011) flux mapping model predicts that the ionospheric mapping of a fixed position in the equator will vary over the course of a Jovian rotation period because of local time asymmetries in the magnetosphere. The model predicts that ionospheric contours that map to a fixed equatorial radial distance will be located more poleward where they map to local times near dusk than where they map to dawn local times, as we illustrate in Figure S1 in Supporting Information S1. This point can also be seen in the middle panel of Figure 7, where the different colored mapped $50 R_J$ contours are shifted poleward near dusk and equatorward near dawn. Since the portion of the main emission that maps to a specific local time rotates with CML, magnetospheric local time asymmetries are manifested in auroral images as a CML-dependent latitudinal shift in the location of the main auroral emission.

We investigate the expected CML dependence in Figure 7, which compares the observed CML dependence of the main auroral emission to the CML dependence predicted using the Vogt et al. (2011) mapping model with JRM09 as the internal field model. Here, we consider the mapping to $50 R_J$, though this distance is at the upper end of the typical main emission radial distance mapping (Figure 10), because the CML dependence we observe in the main emission is larger than the predicted variability at $30 R_J$. This is probably because the main emission mapping varies with local time (Figure 10), which further amplifies the expected CML dependence since a position on the main emission would shift even more poleward when it is linked to dusk local times (where it maps to a larger radial distance) compared to when it is linked to dawn local times (where it maps to a smaller radial distance).

The middle row of Figure 7 shows the ionospheric contours mapping to $50 R_J$ in the magnetosphere at different CMLs corresponding roughly to the average CML of the images included in each bin: in northern hemisphere those CMLs are 120° (purple), 160° (blue), 210° (green), and 270° (red), and in the southern hemisphere they are 30° (purple), 90° (blue), and 330° (red). The black contours in the middle panel of Figure 7 show average modeled mapping contours, which we calculated by averaging the colored CML-specific contours for each hemisphere, using a weighted average accounting for the number of images in each CML bin. Finally, the bottom row of Figure 7 shows the magnetic latitudinal shift between each CML-specific statistical main emission contour and the average statistical main emission contour calculated from all images used in this study. We define the shift as positive if the CML-specific statistical main emission contour is poleward of the average statistical main emission contour and negative if it is equatorward. The solid lines show the observed latitudinal shift, or the magnetic latitude difference between the colored and black contours from the top panel of Figure 7, and the dashed lines show the modeled magnetic latitude shift, or the difference between the modeled colored and black contours from the middle panel of Figure 7.

By comparing the observed (solid) and predicted (dashed) latitudinal shifts in the bottom row of Figure 7, we see that the overall CML dependence observed in the main auroral emission is generally consistent with the CML dependence predicted by the ionospheric mapping from $50 R_J$. For example, both the observations and mapping predictions show a large poleward (positive) shift at longitudes $\sim 200^\circ$ – 240° for CML 240° – 290° in the north (red) and a large equatorward (negative) shift at longitudes $\sim 30^\circ$ – 70° for CML 290° – 360° in the south (red). The observed shifts in the other CML bins do not match the mapping predictions as closely but do generally match the direction of the modeled shift (i.e., poleward or equatorward) and the observed and mapped contours from the various CML bins generally appear in the same order from most poleward to most equatorward. For example, both the observed and modeled shifts at CML 0° – 60° in the southern hemisphere (purple lines) are positive at longitudes -50° – 50° , peaking near $\sim 40^\circ$ longitude then changing sign and remaining negative at longitudes 50° – 90° . In the northern hemisphere, both the observed and modeled shifts at CML 190° – 240° (green lines) are positive at longitudes less than $\sim 200^\circ$ and negative at longitudes larger than $\sim 200^\circ$. Overall, we find that trends in the observed and modeled CML dependence are broadly consistent with each other. Since the auroral mapping model has no temporal dependence this confirms that the observed main emission CML dependence is a real spatial, not temporal, variation that likely results from local time asymmetries in both the magnetosphere and the main emission equatorial mapping.

Finally, we show in Figure 11 the expected variability in the main emission position resulting from changes in the current sheet current density. We represent the main emission position by tracing model field lines from $30 R_J$ in the jovigraphic equator and we assess the expected variability by altering the $\mu_0 I_0$ parameter in the Connerney et al. (1981) current sheet model (“CAN1981”) or the similar Juno-era current sheet model from Connerney et al. (2020; “CON2020”). Both CAN1981 and CON2020 represent the perturbation magnetic field as that produced by an axisymmetric annular disk of azimuthal current with adjustable parameters including the inner edge R_0 , outer edge R_1 , half-thickness D , and current density I_0 . (The CON2020 model additionally included the effects of the radial current which produces the azimuthal magnetic field that sweeps the field back out of the meridian plane.) The blue, green, and red colored contours show the traced $30 R_J$ mapping calculated using varying $\mu_0 I_0$, representing low, average, and high current sheet current density, respectively, in the CAN1981 and CON2020 current sheet models. We implemented the CAN1981 model using the Voyager-era fits for R_0 ($5 R_J$), R_1 ($50 R_J$), and D ($2.5 R_J$), and took $\mu_0 I_0 = 400, 480, \text{ and } 560$ nT, roughly covering the range of Galileo-era fits (406 – 572 nT with a mean of 476 nT) from Vogt et al. (2017). We implemented the CON2020 model using the Juno-era fits for R_0 ($7.8 R_J$), R_1 ($51.4 R_J$), and D ($3.6 R_J$), with the mean value of $\mu_0 I_0 / 2\pi = 16.7$ nT, and took $\mu_0 I_0 = 240, 280, \text{ and } 320$ nT, roughly covering the range of Juno-era fits (248.4 – 312.2 nT with a mean of 279.2 nT) as reported by Connerney et al. (2020).

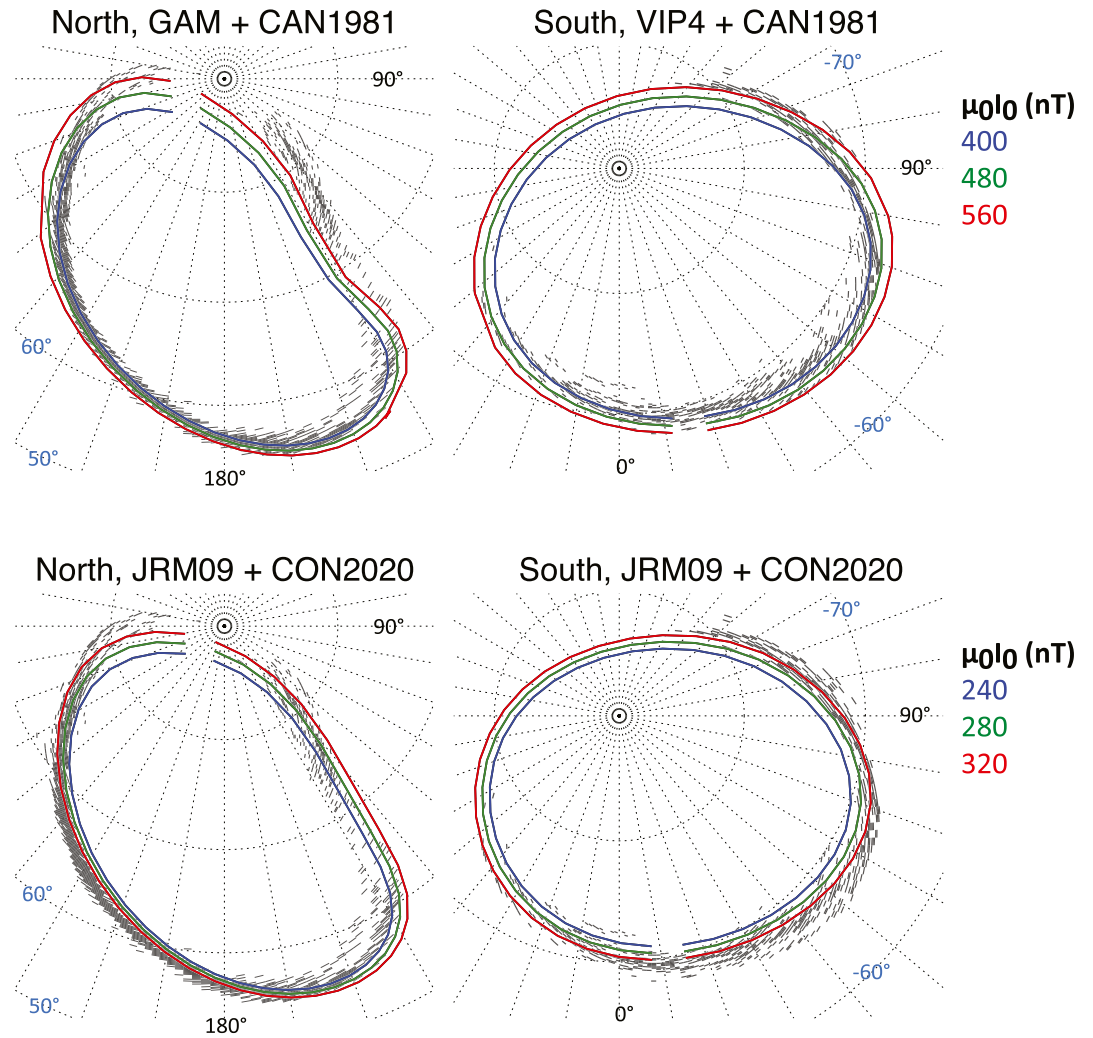


Figure 11. Expected variability in the ionospheric mapping of $30 R_j$ radial distance in the jovigraphic equator, calculated by tracing model field lines for different internal field models (VIP4, Connerney et al., 1998; JRM09, Connerney et al., 2018; GAM, Grodent, Bonfond, et al., 2008) as noted. In the top row field lines were traced assuming the current sheet model of Connerney et al. (1981), while in the bottom row field lines were traced using the current sheet model of Connerney et al. (2020). Blue, green, and red contours show the traced $30 R_j$ mapping calculated using low, average, and high values, respectively, for the $\mu_0 I_0$ parameter in the CAN1981 (top) and CON2020 (bottom) current sheet models (see text). Bins of 2° magnetic longitude by 0.1° magnetic latitude are shaded in gray if the main emission was located in that area in at least two of the images used in this study.

We can compare the variability of the colored contours—representing low, average, and high current sheet current density—to the variability in the main emission position as indicated by the small shaded gray bins of 2° magnetic longitude by 0.1° magnetic latitude. We have shaded in all bins for which the main emission was located in that area in at least two of the images used in this study, which eliminates some of the extreme outliers (see e.g., dark purple high-latitude bins in the distribution of the main emission locations shown in Figure 5). The different panels of Figure 11 show $30 R_j$ fieldline tracing results obtained using CAN1981 plus the internal field of the Grodent Anomaly Model or GAM (Grodent, Bonfond, et al., 2008) in the north and VIP4 (Connerney et al., 1981) in the south and CAN2020 plus JRM09 (Connerney et al., 2018) in both the north and south. There is considerable variation in how well the mapped $30 R_j$ contours of the different field models/options match the main emission locations. However, we can see that the predicted variability in the main auroral emission position as indicated by the spacing of the colored contours is roughly consistent with the observed variability as indicated by the spread of the gray shaded bins.

We conclude that the observed variability in the position of Jupiter's main auroral emission is produced mostly by temporal variability in the magnetosphere (such as changes in the strength of the current sheet), and not by the CML-dependent effects that occur over one Jovian rotation. This conclusion is supported by the discussion above and by two additional arguments: first, Figure 11 shows that changing the current sheet current density affects the mapped ionospheric position roughly equally at all magnetic longitudes, while the CML-dependent mapping in the middle panel of Figure 7 shows very little effect at some longitudes. Second, as shown by the distributions of the observed main emission positions in the right half of Figure 5, the magnitude of the observed main emission latitudinal shifts does not appear to be CML-dependent (though there is some local time dependence).

4.4. Discussion and Future Work

The results described above include some unexpected and sometimes conflicting conclusions about the latitudinal variability of the main auroral emission, its relationship to variability in the Ganymede footprint position, and the influence of changes in the current sheet current density. In particular, the absence of a clear relationship between the Ganymede footprint shift and the concurrent $\mu_0 I_0$ fit by Galileo is puzzling. The most likely explanation is that errors in the planetary limb fitting procedure led to incorrect positions and the derived shifts for both the Ganymede footprint and the main emission. However, it is also important to remember that the limited HST data set considered here, particularly when considering the subset of images that contain the Ganymede footprint, does not encompass times of the most extreme $\mu_0 I_0$ values. We note, for example, that most of the Ganymede footprint shifts measured here are positive, indicating a position poleward of the reference footpath, which would be expected for a weaker than normal current sheet stretching. This is consistent with the fact that the Galileo $\mu_0 I_0$ fits at the time of the HST images ranged from ~ 430 to 500 nT, while the Galileo $\mu_0 I_0$ fits from all orbits ranged from 406 to 572 nT. Finally, we note that the typical Ganymede footprint shift observed here, $\sim 0.5^\circ$ poleward, is roughly consistent with the total difference, $\sim 1.5^\circ$, expected between the strongest and weakest current sheet fits to all Galileo data (top right of Figure 1). In the future, expanding our analysis to include Juno $\mu_0 I_0$ fits (Connerney et al., 2020) and Juno-HST concurrent images could help fill out the range of $\mu_0 I_0$ values under consideration and evince the expected relationship between the Ganymede footprint shift and $\mu_0 I_0$.

As a final explanation for the absent expected correlation between the Ganymede footprint shift and the Galileo $\mu_0 I_0$ fit, we note that it is possible that the time or spatial scales of Jupiter's current sheet variability might be inconsistent with the type of snapshot comparison to HST images that we have attempted here. For example, it is possible that the magnetic field configuration at the time of some HST images was influenced by a transient process like a magnetospheric injection (e.g., Mauk et al., 1999), tail reconfiguration (e.g., Louarn et al., 2014), or solar wind compression (e.g., Vogt et al., 2019) that occurred on a time scale that was short (\sim hours to tens of hours) compared to the ~ 5 – 10 days intervals over which the $\mu_0 I_0$ fits were calculated. Such a transient process could produce a brief Ganymede footprint shift that is inconsistent with the $\mu_0 I_0$ fit. There were some Galileo orbits for which the inbound and outbound $\mu_0 I_0$ fits of each orbit varied significantly, as shown by the handful of points with large error bars in the top panel of Figure 3, but the $\mu_0 I_0$ fit values were generally stable on the ~ 5 – 10 days timescale. The $\mu_0 I_0$ values plotted in Figure 9 are the average values for each orbit but similar plots made using the $\mu_0 I_0$ fits from separate inbound or outbound orbit segments, shown in Figure S2, also do not show the expected relationship between the footprint shift and $\mu_0 I_0$. It is also possible that any magnetic field stretching or compression observed by Galileo is limited in local time and does not necessarily extend to Ganymede's location, which would explain why the footprint shift did not display the expected dependence on $\mu_0 I_0$. As shown in the right side of Figure 2, Galileo was generally located at dusk and nightside local times ($\sim 16:00$ and later) when it was located between 10 and $30 R_J$, the radial distance range over which Vogt et al. (2017) calculated the $\mu_0 I_0$ fits. By comparison, almost all of the Ganymede footprints we analyzed in this study map to earlier local times, roughly $08:00$ – $12:00$. However, we note that the Galileo $\mu_0 I_0$ fits were generally similar for both the inbound and outbound portions of an orbit, which could be at significantly different local times, so we feel this explanation is somewhat unlikely.

The analysis we have undertaken here naturally leads to several interesting topics for future work. Here, we have considered only the auroral position and not other auroral properties like brightness or the width of the main emission, which have been examined by Nichols et al. (2009). As discussed above, our identification of the main emission as a distinct point defined by the peak emission as fit by a Gaussian is almost certainly an oversimplification. Therefore, a future study could assess whether these properties are linked to changes observed in the

magnetodisk or variability in the satellite footprint locations. Computational M-I coupling models like those applied in Nichols (2011) and Nichols et al. (2015) can be used to examine how variability in the CEC system can produce the auroral shifts we have studied here, and model results could be compared to Galileo data. Finally, we hope in the future to more thoroughly analyze the Galileo magnetometer data and additional Galileo data sets like the hectometric auroral radio emissions and energetic particle detector measurements for context about the state of Jupiter's magnetosphere at the time of each HST image. For example, Galileo data can help infer whether, at the time of each HST image, the magnetosphere was experiencing a solar wind compression or other dynamic behavior such as a quasi-periodic interval of magnetic loading/unloading (e.g., Kronberg et al., 2005, 2007; Louarn et al., 2014; Yao et al., 2019), and the measured variability in the magnetic field and plasma properties provide a valuable constraint to M-I coupling models.

5. Summary

We have identified the position of the main auroral emission in all HST images that overlapped with the Galileo mission (1996–2003). We have quantified the variability in the main emission position and compared it to concurrent shifts in the position of the Ganymede footprint and to changes in the current sheet current density $\mu_0 I_0$ fit to concurrent Galileo data. We expect that the position of the satellite footprints will depend on the $\mu_0 I_0$ term, which provides a measure of how radially stretched the magnetic field is, because the satellites are located at a fixed position in the magnetosphere and any motion in their auroral footprints should be linked to a change in the magnetic field configuration. By comparison, past observations have shown that the main auroral emission may shift independently (in magnitude and direction) of the satellite footprints, which would suggest that the variability can be driven by factors in the CEC system or any other mechanism responsible for the main emissions that do not influence the magnetic field geometry.

We compared the magnitude and direction of latitudinal shifts in the main auroral emission and Ganymede footprint and found that the two auroral features generally moved together (i.e., both shifted poleward or both shifted equatorward with respect to a reference contour). However, we also found that the position (with respect to a reference contour) of both the main auroral emission and the Ganymede footprint are only weakly linked to the changes in the concurrent best fit $\mu_0 I_0$. The lack of the expected clear relationship between the Ganymede footprint behavior and the current sheet current density is puzzling and may reflect the uncertainty in the planetary limb fitting during the STIS image processing. Additionally, we found that there can be significant differences in the measured main emission position among images from the same day, even after accounting for the expected variability with CML/over a Jovian day, which is probably also indicative of the measurement uncertainties.

As part of our analysis, we derived a northern and southern statistical main emission reference contours using all images in the north and south hemispheres, respectively, and also derived statistical reference contours using only images from specific CML ranges. We found that the main emission position shifts by $\sim 1^\circ$ – 2° over the course of one Jovian rotation and that the observed CML dependence is consistent with the mapping model predictions that account for local time asymmetries in Jupiter's magnetosphere. Additionally, we mapped our derived statistical main emission reference contour to the magnetosphere using both a flux equivalence and field line tracing technique and found that the main emission typically maps to ~ 20 – $40 R_J$ in the equator and at larger distances near dusk than near dawn.

In summary, we have quantified the temporal and spatial (CML and local time) variability of the main auroral emission and Ganymede footprint during the Galileo era. We do not find a strong link between the auroral shifts and the current sheet current density fit to Galileo data but we expect that future studies will provide more insight into the drivers of the observed auroral variability, both by decreasing the uncertainty in the auroral position and by expanding our analysis to other Galileo and Juno data sets.

Data Availability Statement

This work is based on observations with the NASA/ESA Hubble Space Telescope obtained from the Data Archive at the Space Telescope Science Institute (<https://archive.stsci.edu/hst/search.php>), which is operated by the Association of Universities for Research in Astronomy, Incorporated, under NASA contract NAS5-26555.

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