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Key Points:
- UV emissions from Callisto's auroral footprint detected using HST observations
- Jupiter's main auroral emission was dim and shifted equatorward for the candidate detections
- Callisto's auroral footprint emitted power is similar to that of Ganymede

Supporting Information:
- Supporting Information S1
- Movie S1

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Evidence for Auroral Emissions From Callisto's Footprint in HST UV Images

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Abstract Auroral emissions are expected from the footprint of Callisto in Jupiter's upper atmosphere owing to the known interaction of its atmosphere with Jupiter's magnetosphere, and from the observed auroral emissions from the footprints of the other three Galilean satellites. The mapping of Callisto along modeled magnetic field lines at Jupiter, however, places the expected footprint at the same latitude as the main auroral emissions, making it difficult to detect. We analyzed ultraviolet images of Jupiter taken using the Hubble Space Telescope/Advanced Camera for Surveys instrument during a large observing campaign in 2007. Using a coaddition method similar to one used for Enceladus, we have identified a strong candidate for the footprint of Callisto on 24 May 2007. We tested this finding by applying the same coaddition technique to a nearly identical auroral configuration on 30 May 2007 when Callisto was behind Jupiter, not visible from Earth (central meridian longitude = 22°; sub-Callisto system III longitude = 327°). By comparing the two coadded images, we can clearly see the presence of a strongly subcorotating spot close to the expected Callisto footprint location on 24 May and its absence on 30 May. On 24 May Callisto was located in the current sheet. We also found a probable candidate on 26 May 2007 during which time Callisto was positioned below the current sheet. The measured location and intensity of the auroral emission provide important information about the interaction of Callisto with Jupiter's magnetic field, the corotating plasma, and the neutral and ionized state of the thin atmosphere of Callisto.

1. Introduction

Jupiter has a complex and highly dynamic magnetosphere (Delamere et al., 2015; Khurana et al., 2004; Krupp et al., 2004). The magnetosphere of Jupiter is unique in the solar system because of its large extent and rapid rotation, as well as the large amount of plasma provided by the Galilean satellite Io. Observations from Earth revealed Jupiter to be a source of intense radio emissions that were highly correlated with the orbital position of its satellite Io (Bigg, 1964). It was concluded that an electromagnetic interaction exists between Jupiter and Io that gives rise to these radio emissions from the foot of the Io flux tube in Jupiter's upper atmosphere (Goldreich & Lynden-Bell, 1969; Piddington & Drake, 1968). These electromagnetic interactions between Jupiter and Io produced auroral signatures which were first observed as H_3^+ emissions in the infrared by Connerney et al. (1993) and were referred to as auroral footprints. This was the first satellite footprint in Jupiter's atmosphere to be discovered in the infrared spectral range. Io's footprint has also been observed in the far ultraviolet (FUV) wavelengths (120–170 nm) by Hubble Space Telescope observations (Clarke et al., 1996; Prangé et al., 1996). The Galileo and New Horizons probes have detected the same auroral signature from Io at visible wavelengths (Gladstone et al., 2007; Vasavada et al., 1999). The Europa and Ganymede footprints were discovered simultaneously with the Hubble Space Telescope (HST) at FUV wavelengths (Clarke et al., 2002) and further observations have shown their variable interaction with Jupiter's magnetosphere (Bonfond et al., 2013, 2017; Grodent et al., 2009). More recently, the Jovian Infrared Auroral Mapper instrument onboard the Juno spacecraft has detected H_3^+ infrared emissions from the footprints of not only Io, but Europa and Ganymede as well (Mura et al., 2017). This discovery demonstrates that, like Io, both Europa and Ganymede have persistent interactions with Jupiter's magnetic field despite their thin atmospheres leading to current systems flowing in and out of the Jovian ionosphere.

Theoretical models describing the creation of these auroral footprints include the unipolar magnetic field model (Goldreich & Lynden-Bell, 1969), the Alfvén wave model (Goertz, 1980; Hill et al., 1983; Neubauer, 1980), and the open loop Alfvén model (Crary, 1997; Crary & Bagenal, 1997). These models were mostly based on the observed behavior of Io's auroral footprint emissions in Jupiter's atmosphere. The basic theoretical framework of these models suggests that auroral signatures due to the Galilean satellites are created by high energy charged particles energized at each satellite due to an electric potential created by the relative motion of the satellite with respect to Jupiter's rapidly corotating magnetic field (Belcher, 1987). In addition, the fast corotating plasma in Jupiter's magnetosphere overtakes the much slower satellites that then act as obstacles for the flow of plasma. The combined perturbation from the fast corotating plasma and the electric potential created by Jupiter's magnetic field sweeping past the slowly orbiting satellites propagates along the magnetic field lines as Alfvén waves, which, on their way to the planet, cause the acceleration of electrons in both parallel and antiparallel directions. These electrons precipitate into the planetary atmosphere triggering the auroral emissions (Bonfond et al., 2008; Hess et al., 2010). The detailed process of formation of the footprints is much more diverse and complex than summarized above (Jia et al., 2010; Kivelson et al., 2004; Saur et al., 2004). However, modeling efforts in the past decade that used Alfvén wave propagation effects on precipitating electrons in Jupiter's atmosphere have been used to study the evolution of Io's footprint brightness (Bonfond et al., 2012; Hess, Bonfond, Chantry, et al., 2013; Hess, Bonfond, & Delamere, 2013) and the nature of Ganymede's footprint and the Alfvén wing spots associated with it (Bonfond et al., 2013). The modeling results agree well with observations of the satellite footprint brightness at Jupiter and have also been extrapolated to study planet satellite interactions in exoplanet systems (Hess et al., 2011, Hess, Bonfond, Chantry, et al., 2013; Saur et al., 2013).

The auroral footprints of Io, Europa, and Ganymede have been often observed and are well studied (Bonfond et al., 2012; Bonfond et al., 2017; Clarke et al., 1996, 2002; Connerney et al., 1993; Gérard et al., 2006; Prangé et al., 1996; Wannawichian, Clarke, & Nichols, 2010). These emissions are well separated from the much brighter main auroral emission of Jupiter and can be easily distinguished since they remain close to the magnetic footprints of the satellites while other auroral emissions rotate with the planet. The brightness of ultraviolet H_2 emissions from Io's footprint at times reaches several hundred kiloRayleighs (1 kR = 10^9 photons cm^{-2} s^{-1} into 4π steradians), whereas the emissions from the footprint of Ganymede (which has an intrinsic magnetic field) are a few tens of kiloRayleighs in brightness (Clarke et al., 2002; Dols et al., 2000). Europa's footprint brightness is 5–10 times weaker than Ganymede (Bonfond et al., 2017) but can occasionally get as bright as Ganymede's footprint (Clarke et al., 2002). However, the auroral footprint of Callisto has until now eluded detection due to its proximity to the bright main auroral emission. Furthermore, owing to Callisto's distance from Jupiter (26.93 R_J, the Galilean satellite furthest from the planet) and lack of intrinsic magnetic field that would increase the cross-sectional area of the interaction region with Jupiter's corotating plasma like Ganymede, the associated footprint emission is expected to be faint and difficult to detect (Clarke et al., 2002; Saur et al., 2013). It has also been found that satellite footprints, especially for Io and Ganymede, can dim considerably (Bonfond et al., 2017) when they encounter an auroral injection signature. This could be because during such occasions electron densities are higher than usual in the acceleration region and can suppress electron acceleration by inertial Alfvén waves (Hess, Bonfond, & Delamere, 2013), the main mechanism for generating the auroral footprint signatures. Such an effect could also be hindering the brightness of Callisto's auroral footprint rendering it dim.

At the turn of the century, Menietti et al. (2001) reported the detection of low frequency decametric emissions by the Galileo spacecraft, within the frequency range of 2.0 MHz to 5.6 MHz, which were correlated to the orbital position of Callisto around Jupiter. They have estimated the power of the Callisto-dependent emission to be 70% of the Io-dependent radio emission and about the same as the Ganymede-dependent radio emission, supporting the expected presence of auroral emissions at the Callisto footprint at Jupiter.

The Jovian magnetosphere plasma sheet periodically flaps about Jupiter's centrifugal plane in the north/south direction by a large amount at the distance of Callisto from Jupiter (maximum displacement ~3 R_J), with important implications for conditions at Callisto (Khurana & Schwarzl, 2005). Kivelson et al. (1999) detected an inductive magnetic response in the magnetometer data consistent with an electrically conducting sphere in multiple passes of the Galileo spacecraft by Callisto. These authors suggested that any ionosphere at Callisto was likely to be too low in density to provide the needed conductivity and proposed the presence of a subsurface ocean to account for it. Zimmer et al. (2000) modeled the constraints from a subsurface ocean on Callisto. They found that a highly conductive layer near the surface would be needed to explain the magnetic induction signature, as could be provided by an Earth-like ocean if it were very close to the surface. In another close pass of Galileo by Callisto, the plasma wave instrument detected upper hybrid waves consistent with an ionospheric electron density up to 400 cm^{-3} (Gurnett et al., 2000), which represents a relatively thin, but detectable ionosphere. Radio occultation data from Galileo also indicated the presence of a substantial ionosphere at Callisto (Kliore et al., 2002), with a proposed O_2 atmosphere to support the ionosphere. Recent HST observations of Callisto have found airglow emissions also consistent with an atmosphere dominated by O_2 (Cunningham et al., 2015). More recently, detailed models of Callisto's atmosphere and ionosphere have found that an O_2 atmosphere with densities that are comparable to the other Galilean satellites is consistent with the measurements (Hartkorn et al., 2017).

The Adaptive Ion-Kinetic Electron-Fluid Hybrid simulation model (Müller et al., 2011) was applied to the Galileo data from the C10 flyby, when Callisto was near the center of the Jovian current sheet (Liuzzo et al., 2016), and used to explain subtle magnetic signatures during the flyby. The signatures were consistent with field-line draping and production of Alfvén wings when the spacecraft was at large distances from the satellite. Closer to Callisto, the spacecraft encountered a quasi-dipolar region that was partially shielded from plasma interactions at the boundary of which the magnetic field vector rotated by ~50°. Modeling revealed that these observed magnetic signatures were a result of the coupling between Callisto's plasma interaction and induction within its subsurface ocean (Liuzzo et al., 2016). The spacecraft also encountered large electron density enhancements (3–4 orders of magnitude) in Callisto's wake, consistent with a substantial ionosphere, more than previously expected. These are indications of plasma interactions that would lead to strong field-aligned currents that would close in the Jovian ionosphere, thereby producing a substantially bright auroral footprint signature for Callisto.

This study reports evidence for the detection of emissions from the auroral footprint of Callisto in the FUV wavelength range using observations of Jupiter's aurora obtained by the Hubble Space Telescope in 2007 (Clarke et al., 2009). This detection was made possible due to both a large data set and the application of a coaddition method similar to one previously used for attempting to search for Enceladus's footprint at Saturn (Wannawichian, Clarke, Pontius 2008), applied to the images of Jupiter's aurora and a considerably dimmer than usual main auroral emission. Section 2 describes the observations of Jupiter and the image reduction process. Section 3 elaborates on the coaddition method applied to the HST images in order to increase the signal-to-noise ratio of the auroral footprint of Callisto, as well as the potential candidates identified for the auroral emissions associated with Callisto.

2. Observations and Data Reduction

The Hubble Space Telescope (HST) has been extensively used to image satellite footprint emissions in Jupiter's aurora over the past two decades. The Space Telescope Imaging Spectrograph onboard HST was used to image Jupiter in the FUV wavelength range (115–170 nm) between the years 1997 and 2004, whereas the Advanced Camera for Surveys (ACS) was the instrument most used from 2005 to 2008 to image Jupiter's dynamic aurora in the FUV. The data set used to search for Callisto's auroral footprint composed of two concentrated series of daily observations of Jupiter's aurora using the HST-ACS instrument in 2007. There are a total of 52 observational visits starting from 20 February to 21 March 2007 for the first set of observations and from 13 April to 11 June 2007 for the second set of observations. These images contain observations of both the north and south polar auroral activities at Jupiter.

The data reduction processes include dark image subtraction, flat-field correction, and instrumental geometric distortion correction (described in detail by Nichols et al. (2009) and Clarke et al. (2009)). The reduced images in the form of a 1,400 × 1,400 arrays taken with ACS were scaled to appear at the common distance of 4.2 AU, with the north pole oriented toward the top of the image and the south pole oriented toward the bottom of the image. The final reduced image had brightness expressed in units of kiloRayleighs (kR) per pixel. The absolute calibration of ACS in order to convert photon counts to kiloRayleighs was generated by the synthetic UV spectrum of H_2 and Lyman α emission (Gustin et al., 2012).

The ACS image data set consisted of a series of F115LP and F125LP filter images. In this study, the F115LP images were utilized as they include the Lyman α emission, which also contributes to the auroral emission from Jupiter. This would enhance the signal-to-noise ratio in the images for auroral emissions.

3. Method to Identify Candidates for the Auroral Footprint of Callisto

Both theory and observations support the fact that the auroral footprint of Callisto is much fainter than the footprint of Io. Low frequency decametric emission detected by Galileo found the power of the Callisto footprint emission to be 70% of Io's associated emission (Menietti et al., 2001). Observations of Poynting flux at Io range from 4 to 300 GW, whereas the numbers theorized for Callisto are in the range of 0.0001–5.2 GW (Saur et al., 2013). This has made it difficult to discover Callisto's footprint, along with the fact that it is located much closer to the extremely bright and dynamic main auroral emission of Jupiter. In this study, a new method was developed and used in the image analysis process to increase the probability of discovering Callisto's auroral footprint. This method takes advantage of the fact that the main emission has been observed to shift its position in latitude by several degrees from day to day (Bonfond et al., 2012; Grodent et al., 2008).

The first step in finding Callisto's footprint was to select suitable days in the observational range when the main auroral emission had migrated to lower latitudes or was much dimmer than usual and Callisto was positioned between Earth and Jupiter for visibility of the footprint. Once a suitable day of observation was selected, one could take advantage of the fact that emissions associated with Callisto would remain at the foot of the Alfvén wing, located downstream from the magnetic field line passing through Callisto, while emissions from the main aurora would corotate with Jupiter. The Alfvén travel time from Callisto to Jupiter is ~30 min, whereas the time taken by Jupiter's corotating field to pass by Callisto is ~15 s, making the auroral footprint of Callisto almost stationary in comparison to the main auroral emission.

Upon determining a suitable day of observation, the next step involved finding the expected location of the magnetic footprint using the VIP4 magnetic field model (Connerney et al., 1998). The VIP4 model provides reasonable predictions for the satellite footprint locations at Jupiter and is mainly used to map the Jovian main auroral emissions. However, it is known to become increasingly inaccurate beyond the orbit of Io (Bonfond et al., 2009; Grodent et al., 2008). This is mainly because in the model the current sheet contribution is based on a symmetric and static magnetodisc field. But at distances beyond 25 R_J, where Callisto is located, local time-dependent external field contributions become important. Furthermore, the field lines are distorted due to the interaction of Jupiter's magnetic field with the solar wind. Therefore, in our study, we have used the locations of the satellite footprints predicted by the VIP4 model more as a reference point to explore the general area around it in our search for the auroral footprint for Callisto.

After obtaining a predicted location for Callisto's footprint from the VIP4 model, all the images were projected at 240 km above the 1 bar level to longitude/latitude space, and then shifted both in latitude and longitude using bilinear interpolation, with respect to a reference image, such that the expected locations of the Callisto footprint were overlaid on top of each other in all the images. The reference image was generally taken to be the middle-most image so that any one image does not have to undergo a very large shift. Finally, these shifted arrays were coadded and back-projected to get an averaged image. Since the main auroral emission is rapidly rotating about Jupiter's axis and Callisto and its auroral footprint counterpart are orbiting Jupiter relatively much more slowly, this coaddition method blurs out the main auroral emissions while intensifying the footprint. It thus provides a means to test if a particular emission feature is truly tied to Callisto or is rotating with Jupiter.

3.1. Evidence for the Positive Identification of Auroral Emissions From Callisto's Footprint

By selecting instances when the main auroral emission had either migrated to lower latitudes or was dim and Callisto's footprint was visible from the Earth (i.e., was along the side of Jupiter facing Earth), seven possible days were identified as having ideal conditions for the possibility of detecting Callisto's auroral footprint. Out of the seven, the first day that revealed a good candidate for the detection of auroral emissions from Callisto's footprint was 24 May 2007 (day of year: 144). On this day, the main auroral emission in the southern hemisphere observed by HST was in its expected position but was very dim. Several considerably brighter spots were observed on the left side of the image near the main auroral emission. Using the VIP4 model the approximate location in terms of latitude and longitude positions for each satellite's footprint was identified. This model revealed that Ganymede and Callisto's footprint would be in close proximity to each other in longitude, but well separated in latitude. On this day both Ganymede and Callisto were at system III longitudes of around 90°, while Io was at a much higher orbital longitude. The CML for Callisto was ~17°. This means that Callisto and its auroral footprint were visible from Earth on 24 May 2007.

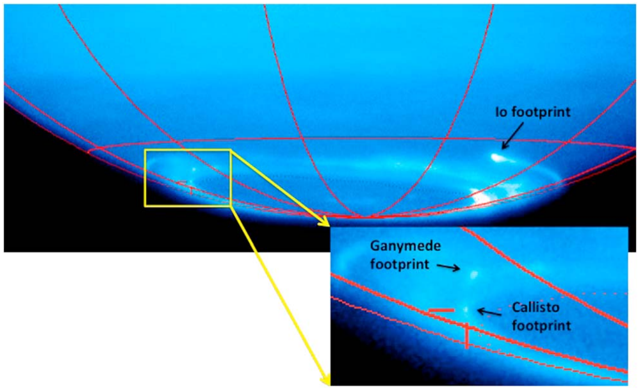

Figure 1. Jupiter's south pole as observed with the ACS instrument of HST on 24 May 2007. This image has been produced by coadding eight consecutive HST observations of Jupiter's south pole aurora on 24 May 2007. The candidate for Callisto's footprint is indicated by the red tick marks near the left ansa. The other bright spot above Callisto's footprint is identified as Ganymede's footprint which was close to Callisto's orbital position on this day. Io's footprint can be seen on the right.

Figure 1 shows the auroral emissions at the south pole of Jupiter as observed by HST on 24 May 2007. This image was created by coadding the eight consecutive HST ACS observations of Jupiter's south pole in the UV with a total observation time of ~17 min. The footprints identified to be associated with Ganymede and Callisto appear on the left of the image, whereas the footprint associated with Io appears on the right. Both the Io and Ganymede footprints have been associated with multiple auroral spots due to the various processes involved in the generation of the auroral footprint (Bonfond, 2012; Bonfond et al., 2013, 2017; Clarke et al., 2002; Wannawichian, Clarke, Nichols 2010).

In order to verify that the identified bright spots in the image obtained on 24 May 2007 were not artifacts of the coaddition method, the same procedure was applied to eight consecutive HST observations of Jupiter's aurora obtained on 30 May 2007 (day of year: 150). On this day, the structure and location of Jupiter's main auroral emission were nearly identical to 24 May 2007, but Callisto's footprint was on the nightside and not visible from the Earth (CML = 22° and Callisto system III longitude position = 327°). A reference image was selected from among the eight, and all other images were shifted in latitude and longitude space by the same amount as the 24 May 2007 images before coaddition. The reference image was generally taken to be the fourth image in the observing run sequence to optimize the total shifting that would be undergone by all the images. The effect of coadding the images obtained during the observational run on 30 May 2007 blurred the aurora as expected and did not produce any bright spots as seen on 24 May 2007. Figure 2 shows the coadded image with the blurred main auroral emission for the 30 May observations with HST. No bright spots are visible in the image. This verifies that the bright spots in the aurora could be evidence for the footprint of Callisto, implying a relative motion consistent with Callisto's orbital location and magnetic mapping to the planet. Other explanations for the bright spot could be localized limb brightening of the main emission in the ansae or polar dawn spots, which are mostly found between 04:00 and 09:00 local time meridians (Radioti et al., 2008). However, the spots are consistent in brightness and position in the entire set of eight individual images obtained with HST on 24 May 2007 and are very faint (160–220 kR), whereas a limb brightened main auroral emission with brightness above 1,000 kR is observed on the right for each image, rendering it likely that the spots are associated with satellite footprints.

The candidate Callisto auroral footprint emission feature identified from HST images obtained on 24 May 2007 measured three pixels in diameter. Because of its proximity to the main auroral emission it becomes difficult to distinguish a clear outer boundary for the candidate footprint. In terms of the angular resolution of ACS onboard HST, the angular diameter for the candidate footprint corresponds to 0.075 arcs s, which is similar to the angular resolution implying an unresolved source. The brightness of the candidate footprint was determined by averaging a 3 × 3 box surrounding the brightest pixel and was calculated to be ~183 kR, which corresponds to a power of ~1.5 GW (~30 mW m^{-2}). The background emission, which is mainly reflected sunlight in UV wavelengths, is estimated by a plane fit to the pixels immediately surrounding the 3 × 3 box containing the brightest pixels, which is considered to be Callisto's auroral footprint. The location of the candidate auroral footprint of Callisto was found to be at −70.29° latitude and 87.32° longitude. The VIP4 model and the current sheet model predicted the location to be −67.23° latitude and 68.60° longitude for 24 May 2007. This large difference in longitude may be due to varying conditions in the current sheet surrounding Jupiter, which are quite important at the distance of Callisto.

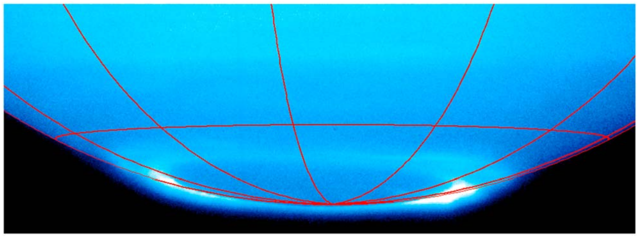

Figure 2. Control case on 30 May 2007, when Callisto was far from dawn. Eight images were shifted and coadded to produce this image just as in Figure 1, and no footprint emission was detected.

Another potential candidate for Callisto's auroral footprint was identified on 26 May 2007. This time Callisto was positioned more along the line of sight connecting Earth and Jupiter (central meridian longitude (CML) = 8° and Callisto's system III longitude position = 42°), free of limb brightening effects, and the identified position of its corresponding auroral footprint by the VIP4 model is approximately in the middle part of the image containing emission from the main auroral emission. On this day, it was again possible to identify a candidate footprint for Callisto against the backdrop of the main emission, due to the dim main auroral emissions near the position of the footprint. However, the brightness of the main auroral emission varied over the series of images taken on this day, and the changing background makes it difficult to clearly identify the bright spot as being the magnetic footprint of Callisto (supporting information). Figure 3 shows the candidate footprint detected for Callisto on 26 May 2007. This image is a single frame unlike Figures 1 and 2. This is because the candidate footprint was located inside the main auroral emission whose morphology was changing rapidly. Therefore, coadding the images blurred out the candidate footprint. The detected footprint location was found to be approximately −70° latitude and 36° longitude, whereas the position predicted by the VIP4 model was −66.82° latitude and 37.68° longitude, well within the uncertainty of the VIP 4 model.

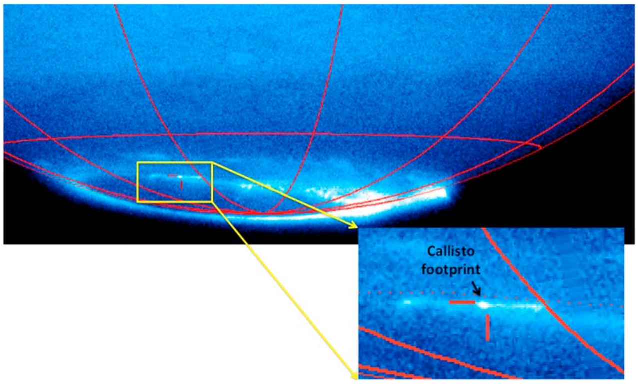

Figure 3. Possible detection of Callisto's footprint on 26 May 2007. Due to the varying brightness of the main auroral emission, the footprint-like feature gets gradually masked by the main emission over the series of images taken on this day. Therefore, we have considered only the first image for this case.

One can estimate the position of Callisto with respect to the Jovian current sheet at the times of these observations. The magnetic axis of Jupiter is tilted by 9.6° from the spin axis toward a system III longitude of 201.7°. It is also offset by 0.131 R_J (9,365 km) toward 148.57° in the system III longitude in a direction 8° below Jupiter's spin plane (Acuña et al., 1983). Jupiter's current sheet has been found to be aligned with the magnetic axis between 10 and 30 R_J, the region in which Callisto is located with a hinged structure (Behannon et al., 1981; Khurana & Schwarzl, 2005). On 24 May 2007, the day of a possible detection of Callisto's magnetic footprint, the sub-Jupiter longitude below Callisto was 88°, thereby positioning it almost centered in the current sheet. On this day, the main auroral emission had shifted downward in latitude and was quite dim in general. Since Callisto was positioned in the current sheet, the effects of this current sheet on Callisto would most likely have been at a maximum on this day producing a bright auroral footprint as has been observed in the case of Io (Wannawichian et al., 2013). On 26 May 2007, another possible candidate for Callisto's magnetic footprint was detected. The sub-Jupiter longitude below Callisto was ~42°, positioning Callisto beneath the current sheet from Jupiter's magnetic axis plane ($z = {\sim}3\ R_J$), which might be expected to produce a relatively weaker interaction and fainter auroral footprint.

4. Discussion

The brightness of the candidate Callisto magnetic footprint detected on 24 May 2007 is ~183 kR, which corresponds to a power of ~1.5 GW (~30 mW m^{-2}). The footprint power falls within the range of theoretical predictions (0.0001–5.2 GW) made for Callisto (Saur et al., 2013). The brightness of Europa and Ganymede's footprint also lies in the few tens of kilo-Rayleigh range (Clarke et al., 2002). Io's footprint brightness is in the hundreds of kiloRayleigh range with its footprint power reaching up to 10^{11} W (Clarke et al., 2002). This input power is more than a magnitude brighter than Callisto (1.5 GW as calculated here), even though it is the smallest among the Galilean satellites. This is mostly because of the large amount of plasma present around Io generated by the numerous volcanic eruptions taking place on the satellite resulting in a large (tens of GW) local power input to Jupiter's upper atmosphere and ionosphere (Clarke et al., 2002; Saur et al., 2013). Another important reason is the stronger magnetic field at Io because it is closer to Jupiter. The calculated electric potential across Callisto is also smaller by a factor of ~7 in comparison to Io. Table 1 provides information about some of the basic parameters on the Galilean moons of Jupiter for 24 May 2007.

Ganymede and Europa's electron input energies range between 0.1 and 15 GW (Saur et al., 2013). Their brightness at H_2 emission wavelengths is higher corresponding to an emitted power in the Giga Watt range (Bonfond et al., 2017). However, Ganymede's magnetic footprint emission brightness has been observed to be brighter than what was expected from the decreased strength of Jupiter's magnetic field at its orbital distance, with its power varying between 0.2 and 1.5 GW (Grodent et al., 2009). This has been attributed to the presence of an intrinsic magnetic field and an external magnetosphere at this satellite, the presence of which

Table 1
South Pole Observing Parameters on 24 May 2007

Name of satellite	Distance from Jupiter (R_J)	VIP 4		Magnetic field ($\times10^{-9}$ Tesla)	Field velo city (km/s)	Radius (km)	EMF (KV)
		Lat.	Lon.				
Io	6.04	−63.76°	350.27°	1,834.49	56	1,821.6	374
Europa	9.60	−65.80°	86.92°	422.98	117	1,560.8	154
Ganymede	15.31	−65.97°	69.20°	90.84	187	2,631.2	89
Callisto	26.93	−67.23°	68.70°	32.45	328	2,410.3	51

would increase the interactional cross-sectional area, thereby increasing the induced potential, making it comparable to Io (Kivelson et al., 1996). Callisto's footprint brightness estimated from the 24 May 2007 observation presented here seems to be on par with Ganymede. However, no intrinsic magnetic field has been detected at Callisto. Instead, a substantial ionosphere of the order of 400 cm^{-3} (similar to that at Ganymede) created mostly by photoionization has been detected at Callisto (Seufert, 2012; Liuzzo et al., 2015). This plasma is then expected to react with Jupiter's magnetosphere to create Alfvén wings (Liuzzo et al., 2016), resulting in the production of ultraviolet emissions from electrons precipitating into the atmosphere, creating a substantially bright auroral footprint. Nevertheless, it is not possible to conclusively estimate the brightness of Callisto's footprint from the single case presented here, as satellite footprints have been known to vary significantly based on the plasma environment in Jupiter's magnetosphere (Bonfond et al., 2012, 2013; Grodent et al., 2009).

At Callisto's distance from Jupiter, the interaction between Callisto's ionosphere and Jupiter's magnetosphere is highly variable compared to the other Galilean satellites. The magnetospheric field intensity varies between 4 and 42 nT, the relative velocity of the plasma sheet with this moon varies between 122 and 272 km/s, and the ion density varies between 0.01 and $0.5 \times 10^6\ \mathrm{m}^{-3}$ (Kivelson et al., 2004). This results in Alfvén Mach numbers that range between subsonic (0.02) and supersonic (1.85) conditions, with changes due to the varying position of Callisto with respect to Jupiter's magnetospheric plasma sheet (Kivelson et al., 2004; Seufert, 2012). In comparison, the relative velocity of Jupiter's magnetospheric plasma has been found to be sub-Alfvénic at Ganymede (Neubaur, 1998). On the days of a possible detection of Callisto's magnetic footprint, presented in this paper, Callisto was either located in the current sheet or below it. However, the most plausible detection on 24 May 2007 was when Callisto was positioned in the current sheet, possibly maximizing the sheet's effect and resulting in a brighter footprint emission, as observed in the case of Io (Wannawichian et al., 2013).

Callisto's magnetic footprint candidates are located at very high latitudes, exactly where the main auroral emission is bright and active. This has made it difficult to identify the magnetic footprint of Callisto over all these years. However, in the two cases described in this paper, it was observed that only when the main auroral emission is either dim or shifted in latitude, there is a possibility of detecting Callisto's auroral footprint.

5. Conclusion

The locations and the observed brightness of the auroral footprints for the three Galilean moons of Jupiter, Io, Europa, and Ganymede, have been used as a valuable constraint for building Jovian magnetic field models (Connerney et al., 1998; Hess et al., 2011; Vogt et al., 2011). The discovery of Callisto's magnetic auroral footprint would help constrain these models further, especially at large distances from Jupiter, where the model predictions are highly uncertain due to a weak field influenced by the variable azimuthal currents. It would also help provide further insight into the plasma region around Jupiter at Callisto's distance of ~ 26 R_J.

Earlier efforts of identifying the auroral footprints of the Galilean moons have yielded positive results for Io, Europa, and Ganymede but failed for Callisto. One of the main reasons for this is Callisto's footprint is thought to be located at high latitudes where the main auroral emission is present. Due to the overwhelming brightness of the main auroral emission, it has been impossible to detect the footprint of Callisto so far. However, from a large HST observing campaign in the UV in 2007, it has been possible to identify two probable candidates for the magnetic footprint of Callisto. From these two possible detections, we have learnt that the most favorable condition for such a discovery is when either the main auroral emission is dim for a period longer than the observing time or it has shifted to lower latitudes during the observations.

The large observed brightness of Callisto's footprint is likely facilitated by substantial amounts of plasma generated by photoionization, which then propagates down magnetic field lines near Callisto. The electric field potential calculated at Callisto is an order of magnitude lower than Io (Table 1). It is also calculated to be lower than Europa and Ganymede. However, the values listed in Table 1 are approximations based on model calculations of the strength of Jupiter's field and approximations of the plasma velocity relative to the satellites and are therefore highly uncertain. It is difficult to conclude the exact characteristics of Jupiter's magnetic field from the observations of Callisto's footprint presented in this paper due to the high uncertainty involved with their detection. Further observations of Jupiter's aurora and more detections of Callisto's auroral footprint, keeping the conditions for the present candidate detections in mind, would provide more statistically significant results about the characteristics of Callisto's auroral footprint. This would allow for a better understanding of the magnetic field, and the plasma environment around Jupiter and the Juno mission is well poised to do so in the near future. The European JUICE mission will also be able to study this interaction in the coming decade.

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