Relation of Jupiter's Dawnside Main Emission Intensity to Magnetospheric Currents During the Juno Mission

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Abstract We compare Jupiter's dawn-side main auroral emission intensity observed by the Hubble Space Telescope with the simultaneous magnitude of the dawn-side magnetospheric equatorial radial current as observed by Juno during Orbits 3–7. We show that the peak auroral intensity and the square of the radial current per radian of azimuth are strongly correlated with \( R \approx 0.9 \), and that the chance that the two phenomena are unrelated is negligible. We also fit empirical profiles of the total radial current flowing per radian of azimuth to the observed values and estimate the precipitating electron energy flux during each observation, and show this exhibits a similar correlation to the current. We find 1 mW m\(^{-2}\) of precipitating energy flux is associated with \( \sim 5–11 \) kR of auroral emission, consistent with modeling studies. This is the first demonstration of a statistical relationship between the intensity of Jupiter's auroras and the strength of the magnetospheric currents, specifically the radial current, the \( j \times B \) force of which accelerates plasma in the sense of planetary rotation. This result provides compelling evidence that the magnetosphere-ionosphere coupling current system at Jupiter plays a key role in powering the planet's dawn side main auroral emission. We further show that there is no association between the auroral intensity and the rate of change of the magnetic energy density outside the current sheet.

Plain Language Summary Jupiter possesses the brightest auroras in the solar system, over a thousand times brighter than the Earth's. For over two decades, the standard theory to explain the main auroral emission on Jupiter was as a result of the planet's fast rotation, coupled with emission of many hundreds of kg per second of sulfur and oxygen from the volcanic moon Io. This material is propelled away from Jupiter by the rapidly rotating planetary magnetic field, and as it does so its rotation rate slows due to conservation of angular momentum. Jupiter attempts to keep the material rotating at its rotation rate via a system of electric currents flowing through the planet's ionosphere and magnetosphere, which transfer momentum to the magnetospheric plasma. The electric current flowing out of the planet's atmosphere was thought to drive the auroras, however when Juno arrived at Jupiter, little evidence of an electric current system was reported and the above scenario was questioned. Here we compare Hubble Space Telescope observations of the brightness of the main aurora with Juno observations of the amount of current flowing in the magnetosphere and show they are strongly correlated, providing compelling evidence that Jupiter's auroras are driven by magnetosphere-ionosphere coupling currents.

1. Introduction

The principal characteristics of Jupiter's space environment are governed by the planet's strong magnetic field and rapid rotation combined with the major source of plasma at the moon Io, which orbits deep within the magnetosphere at \( \sim 6 \) R\(_J\) (where, the planet's equatorial 1 bar level radius 1 R\(_J\) is 71,492 km). The centrifugal outflow of the plasma originating from Io, and its interaction with the planet through a large-scale magnetosphere-ionosphere (M-I) coupling current system, has for two decades been thought to be the origin of the planet's spectacular main auroral emission (Cowley & Bunce, 2001; Hill, 2001; Southwood & Kivelson, 2001). The main emission, or main oval, is a consistently present feature of Jupiter's complex far-ultraviolet (FUV) auroral morphology and is often the brightest component (Clarke et al., 1998; Clarke et al., 2009; Grodent, Clarke, Kim, et al., 2003). It consists of a few-degree-wide band of emission at \( \sim 15^\circ \) magnetic co-latitude, with intensities typically a few hundred to low thousands of kiloRayleighs (kR), but sometimes considerably brighter. Though broadly stable in form, its overall brightness can change on the timescale of hours (Nichols, Badman, et al., 2017; Nichols, Clarke, Gérard, Grodent, & Hansen, 2009). In addition, its intensity is not uniform, with smaller scale patches and arcs exhibiting variations on timescales as short as a few minutes (Nichols, Yeoman, et al., 2017; Palmraerts et al., 2014). Occasionally, “dawn storms” occur in which the dawn side of the main emission brightens considerably, up to several
tens of MR (Ballester et al., 1996; Clarke et al., 1998; Gérard et al., 1994), and bright small-scale patches are
sometimes observed superposed on the main emission (Gray et al., 2016), thought to result from inward radial
transport of hot plasma following reconnection on the nightside. Overall, however, the dominant paradigm for the
generation of the main oval is as a manifestation of the M-I coupling current system as indicated above.

The theoretical underpinning for this picture, which was initially referenced to Pioneer, Voyager, and Galileo
data, had become largely accepted prior to the arrival of the NASA Juno spacecraft at Jupiter. Much work has
since developed the basic theory in a number of directions (Cowley et al., 2002, 2005; Nichols, 2011; Nichols
& Cowley, 2003, 2004, 2005; Ray et al., 2010, 2014; Smith & Aylward, 2009; Tao et al., 2009) but the principal
idea is as follows. As the ionogenic plasma diffuses radially outward, a tendency to conserve angular momentum
results in a radial gradient in its angular velocity. When mapped along magnetic field lines into the ionosphere,
this reduced angular velocity induces an equatorward electric field in the rest frame of the ionospheric neutrals,
and an equatorward Pedersen current flows, the $\mathbf{j} \times \mathbf{B}$ force of which balances ion-neutral drag. This torque is then
communicated to the magnetospheric plasma via the sweep-back of magnetic field lines out of meridian planes,
with the Pedersen current forming part of a large-scale current system as illustrated in the schematic in Figure 1,
including an equatorial radial component and field-aligned components. The $\mathbf{j} \times \mathbf{B}$ force of the equatorial radial
component acts in the sense of planetary rotation and accelerates magnetospheric plasma back toward corotation,
while the upward field-aligned current, carried by downward-accelerated electrons, is thought to excite the main
auroral oval.

Though this picture was well established by the time of the arrival of the NASA Juno spacecraft at Jupiter, this
mission, along with associated Earth-based remote sensing programs, has provided the first opportunity to test
these ideas in detail. Surprisingly, initial studies arising from Juno’s first passes over the Jovian auroral region
reported little evidence of field-aligned currents and “inverted-V” plasma structures associated with an accel-
erated electron population (Allegrini et al., 2017; Connerney, Adriani, et al., 2017; Mauk et al., 2017; Szalay
et al., 2017), leading to a debate about the importance of corotation enforcement in powering Jupiter’s main
auroral oval (Bonfond et al., 2020). However, recent studies have presented evidence for such features on au-
roral field lines (Kotsiaros et al., 2019; Mauk et al., 2020), with for example, the $\sim 200–300$ nT strength of the
field-aligned current signatures being consistent with theoretical expectations of M-I coupling currents (Cowley
et al., 2008, 2017). Louarn et al. (2016) had shown a correlative relationship between Jovian radio intensity and
azimuthal magnetic field strength, indicating a link between auroral power and azimuthal torque, but that study
did not illustrate which (if any) auroral component was responding. Recently, Nichols et al. (2020) presented a
case study of an enhancement of Jupiter’s auroral emission observed with the Hubble Space Telescope (HST)
during the Juno Orbit 11 inbound pass along with enhanced sweep-back field $\mathbf{B}_\phi$ associated with an elevated
radial current, the $\mathbf{j} \times \mathbf{B}$ force of which acts to accelerate plasma in the sense of planetary rotation as discussed
above. This result provided the first direct evidence that variations in the intensity of Jupiter’s main auroral oval
are associated with changes in the strength of the M-I coupling currents.

Figure 1. Schematic showing a cut through a meridian plane of Jupiter’s inner and middle magnetosphere. The solid lines
show the magnetic field lines, while the dashed lines show the magnetosphere-ionosphere coupling currents. The sense of
azimuthal field produced by the field-perpendicular currents is indicated as labeled. From Cowley and Bunce (2001).
Though illuminating, the observations considered by Nichols et al. (2020) comprised a single event, such that it remains unclear whether there exists a consistent relationship between the radial current and the main emission intensity. Here, we therefore undertake a broader study of the association between Juno magnetic field observations in the middle magnetosphere and Jupiter’s dawnside main auroral oval intensity during the first 14 orbits of Juno’s mission. The results present a compelling ($R \approx 0.9$) correlation between the two phenomena. We also consider the effect of a separate large-scale partial ring current (PRC) system which is primarily azimuthal but has a source at dusk and a sink at dawn, thus on the dawn side potentially contributing to either the observed outward radial current if it closes wholly within the equatorial plane, or to the ionospheric field-aligned current density if it closes via field-aligned currents (Bunce et al., 2002; Connerney et al., 1981, 2020; Khurana, 2001; Lorch et al., 2020). However, we show that subtracting these potential contributions to the inferred currents has little bearing on the results. A number of the key points of Bonfond et al. (2020) relate to inconsistencies between observations and the results of steady-state axisymmetric models, such as dawn-dusk asymmetries and the existence of small-scale features not described by 1D models. However, they also point to the work of Yao et al. (2019) (hereafter, Y19), who discussed Juno measurements of the magnetospheric magnetic field and plasma simultaneous with HST observations of Jupiter’s FUV auroras obtained during Orbit 5 inbound in March 2017. These authors proposed that the intensity of Jupiter’s main emission is directly governed instead by the rate of change of magnetic energy density outside of the current sheet, with brighter auroras observed at the beginning of (or just prior to) intervals of declining magnetic energy, termed “magnetic unloading” events by Y19. We thus also systematically compare auroral intensity with the contemporaneous rate of change of the magnetic energy density over the same interval, and find no significant relationship between the two. Overall, these results provide significant insight into the processes that drive Jupiter’s main auroral emission.

2. Data

2.1. Hubble Space Telescope Data

The auroral observations used in this study were obtained using the Space Telescope Imaging Spectrograph (STIS) onboard HST. Images of Jupiter’s FUV auroras were obtained in program GO-14634 (Grodent et al., 2018), in visits each of length 1 HST orbit, using the F25SRF2 filter, which admits light in the H$_\alpha$ Lyman and Werner bands. For each visit, approximately 250 images with 30 s integration times were extracted from the time-tag data, and reduced and projected onto a planetocentric map in units of kiloRayleighs (kR) using the Boston University pipeline, which has been used extensively in previous studies (e.g., Clarke et al., 2009; Nichols, Clarke, Gérard, Grodent, & Hansen, 2009; Nichols, Yeoman, et al., 2017; Nichols et al., 2020). We converted counts to kR of H$_\alpha$ Lyman and Werner emission over 70–180 nm using the values given by Gustin et al. (2012) as a function of color ratio; here we focus on the narrow main emission, shown by Gérard et al. (2018) to exhibit an FUV color ratio of 10–20, and we employ a value of 16. A gallery of representative images is shown in Figure 2 and all images used are shown in a similar format in the Supporting Information S1.

We have employed northern hemisphere images from program GO-14634 when Juno was in the radial distance range 27–100 R$_J$ up to Orbit 7, by which time the local time (LT) of Juno had progressed from ~6 to ~4.3 h LT. Jupiter’s large-scale currents vary with LT (Khurana, 2001; Lorch et al., 2020), such that minimizing differences in LT between in situ and auroral measurements is important for plausible comparisons. In this study, the magnetic field data are compared with auroral emission intensities at auroral local times (ALT) of ~5–9 h (see below), and while some difference is thus unavoidable, this interval with a maximum LT difference of ~1–4 h facilitates a credible comparison between the magnetospheric magnetic field and the auroral data. For example, Khurana (2001) showed that $B_z$ is similar at all radial distances between 3 and 6 LT, with larger differences between 0 and 3 h LT and, outside 45 R$_J$, 6–9 h LT. We also note that ALT does not take into account the mapping between the equatorial magnetosphere and the planet along swept-back magnetic field lines, such that the auroral region considered will actually map to earlier LTs in the equatorial region. As a simple estimate of the magnitude of the difference, integration along a Nichols et al. (2020) model field line mapping to the edge of the current sheet at $z = 3$ R$_J$ at 50 R$_J$, assuming $pB_z = $ constant along the field line between the current sheet edge and the ionosphere, yields a LT difference of ~0.5–2 h between the ionosphere and the current sheet for the range of $B_z$ values observed, reducing the LT difference between the auroral region and in situ observations to an estimated ~0–2 h. We note that we have also extended the analysis described below with data up to Orbit 14, by which time Juno had progressed to ~2.5 h LT, including an extra five data points, with only marginal change in the results.
Overall, the mean dawnward component of Juno's radial position at the times of the considered HST observations is $\sim 59 \, R_J$, with a mean anti-sunward component of $\sim 20 \, R_J$. As a comparison, at this nightside distance the corresponding 10%–90% percentile range of the dawnward position of the Joy et al. (2002) magnetopause is 80–145 $R_J$. The inner radial distance limit of 27 $R_J$ is discussed further below. We employ only images of the northern auroras for several reasons. First, there are far more images of the north than the south, providing better statistics for comparison with Juno data. Second, the view from Earth of the well-defined portion of the main emission is more complete in the north owing to the non-dipolar nature of Jupiter’s internal field. Third, Juno’s trajectory during the interval considered is such that it provides complete coverage of the northern hemisphere magnetic field just outside the current sheet at the time of each observation. Five HST visits that would otherwise meet the criteria were excluded from the main analysis, visits 25, 36, 88, 30, and 31. The first three of these exhibited dawn storms, when the dawnside main emission was significantly brightened. The origin of dawn storms is unclear but recent suggestions relate to nightside reconnection (Swithenbank-Harris et al., 2021; Yao et al., 2020), rather than more directly to the M-I coupling current system. The other two excluded images were obtained when Juno was outside of the magnetosphere, such that no simultaneous current measurements could be made.

We have projected the images into a coordinate system relative to the Nichols, Badman, et al. (2017) statistical oval using the method described by Nichols, Yeoman, et al. (2017), such that one axis represents position around the oval, and the other is locally perpendicular. Taking the mean along a section of the former axis then yields a mean intensity profile versus magnetic latitude for that section. Hence, for each image, we have obtained the mean 6°-wide latitudinal profile over a 45° swathe eastward from 6 h ALT as defined by the Grodent et al. (2004) ALT system. This covers a significant fraction of the observed portion of the well-defined main emission as termed by Nichols, Badman, et al. (2017), which is most often seen on the dawn side from HST owing to the Earth-based viewing geometry bias. The extraction region so-defined is shown for the images in Figure 2 by the red boxes. The observation angle of this region varies modestly with Earth’s season and with CML owing to the dipole tilt, but is broadly fixed relative to the limb, such that any changes in limb brightening are small and not a dominant factor in the variation of the intensity values calculated below. Limb brightening factors are not well understood but a simple estimate was given by Grodent et al. (2005) as the inverse of the cosine of the observing angle $\mu$. We have hence replicated the analysis below, instead using intensities multiplied by $\mu$, and find the correlation coefficients are unchanged to two significant figures. For each visit, we have co-added the latitudinal profiles for each image to obtain one mean intensity profile versus latitude. Only two visits have images in which a portion of the extraction region lies beyond the limb, and which of course does not contribute to these mean profiles. The mean intensity profiles computed for each of the examples in Figure 2 are shown in Figure 3. For each profile, we obtained 4 different measures of the activity of the main emission. First, we have extracted the peak of the intensity $I_{UV\max}$ of the mean profile as shown by the crosses in Figure 3, which, as we discuss below, is the characteristic value most directly relatable to radial current magnitude. Second, we have computed the mean of the maxima measured for each ($\sim 250$) individual image profiles obtained during each visit. However, the
resulting correlation coefficients obtained using this method differ from those for the first by only \( \sim 0.01 \), so for brevity we do not discuss these results further. Third, we have computed the integral of the intensity over a fixed \( \pm 1^\circ \) width relative to the peak, and finally the integral of the intensity over the FWHM of the latitudinal profiles. These two regions are shaded blue and green, respectively, in the example profiles in Figure 3. For all these methods, uncertainties are given by the standard deviation of the results for each individual image profile obtained during each visit. We now turn to a discussion of the magnetic field data, from which the currents are computed.

2.2. Magnetic Field Data

We employ 60 s averaged magnetic field data from the Juno Magnetic Field Investigation (MAG; Connerney, Benn, et al., 2017), converted to cylindrical \((\rho, \phi, z)\) coordinates aligned with the JRM09 magnetic dipole (Connerney et al., 2018), and with the JRM09 internal field model subtracted to leave the residual field produced by external currents. A close-in view of a representative interval of such data from Orbit 5 is shown in Figure 4, while the wider Orbit 5 interval is shown in Figure 5. We use Orbit 5 as our highlighted interval since it contains eight HST observations (and was primarily employed by Y19), but similar plots for all the intervals considered here are available in the Supporting Information S1. In Figure 4a we first show the azimuthal magnetic field \( B_\phi \), which is of principal importance for the comparison with auroral intensities, being associated with the radial current. That this \( B_\phi \) arises principally from a thin equatorial current sheet is evident from the form of the profile, which rapidly reverses in sense across the sheet and broadly plateaus in magnitude a few \( R_J \) from the magnetic equator. We note that in the dawn sector the confinement of the planetary magnetic field by the solar wind flow will also produce a reversing \( B_\phi \) field having the same sense as the current sheet field, though varying on a larger \((\text{magnetosphere-size})\) north-south spatial scale. In Appendix B we estimate the strength of this field, the curl-free magnetospheric fringing field of the magnetopause-tail current system, using a simple theoretical model, and show that in the vicinity of the middle magnetosphere current sheet magnitudes will typically be a few tenths of a nT, an order of magnitude smaller than the \( \sim 5 \) nT fields employed in this study. Thus in common with previous related analyses of middle magnetosphere fields (Bunce et al., 2002; Khurana, 2001; Lorch et al., 2020), we do not consider such minor contributions further here.

Since, \( B_\phi \) reverses in sense about the current sheet, its value drops to zero as the spacecraft periodically passes through the current sheet. Figure 4d shows the spacecraft displacement \( z_{cs} \) from the current sheet center according to the model of Khurana (1992), from which it can be seen that the field zeros agree with expected times when \( z_{cs} \approx 0 \). Away from the current sheet edge, the values of \(|B_\phi|\) shown in Figure 4a increase with latitude. This can be understood from the application of Ampère’s law to a loop threading the current sheet, which, at the edge of the current sheet yields the current per radian of azimuth flowing within the current sheet. At further distances,
the inferred current per radian consists of the current flowing within the current sheet together with the field-aligned current flowing between the point of measurement and the current sheet (see Figure 1), equivalent to the current per radian flowing in the current sheet at the (larger) radial distance at which that field line meets the current sheet. Thus, in order to infer the current per radian flowing in the current sheet at that radial distance and time of observation, we select data points at the edge of the current sheet with the following algorithm. First, we obtain the rolling mean of the $B_\phi$ data with a 60 min window and then smooth with a Hanning window of width 60 min. This profile is shown by the dashed line in Figure 4a. We then take the first and second derivatives of the smoothed $B_\phi$ profile, $B_\phi$ in nT h$^{-1}$; (c) the second time derivative $B_\phi$ in nT h$^{-2}$; and (d) the axial (z) distance from the Khurana (1992) current sheet. The identified peaks in $B_\phi$ are shown by the crosses in panel (c), and the selection intervals are then shown by the vertical gray bars with highlighted data points in each panel. The solid line in panel (a) shows the cubic splines fitted to the averages of the selected values, which are shown by the crosses. The horizontal gray region in panel (d) shows $|z_{CS}| < 3 R_J$. Local time in decimal hours is shown along with r at the bottom. The magnetic field components are displayed in coordinates referenced to the JRM09 magnetic dipole axis.

Figure 4. Plot showing Juno MAG measurements of the magnetic field and the spacecraft height above the current sheet versus radial distance in $R_J$. Specifically, we show (a) the azimuthal field $B_\phi$ in nT (dots) and the smoothed rolling mean as described in the text (dashed line); (b) the first time derivative of the smoothed $B_\phi$ profile, $B_\phi$ in nT h$^{-1}$; (c) the second time derivative $B_\phi$ in nT h$^{-2}$; and (d) the axial (z) distance from the Khurana (1992) current sheet. The identified peaks in $B_\phi$ are shown by the crosses in panel (c), and the selection intervals are then shown by the vertical gray bars with highlighted data points in each panel. The solid line in panel (a) shows the cubic splines fitted to the averages of the selected values, which are shown by the crosses. The horizontal gray region in panel (d) shows $|z_{CS}| < 3 R_J$. Local time in decimal hours is shown along with r at the bottom. The magnetic field components are displayed in coordinates referenced to the JRM09 magnetic dipole axis.
to those in the north. Since, measurement times often differ from the HST observations by a few hours, a method of estimating values between the selection intervals is required, and for this purpose we fit a cubic spline to the magnetic field data. The cubic spline is fitted to the mean of the values observed during each excursion north of the current sheet center, usually comprising two passes (northward and southward) through the selected height range as illustrated by the line joining the black bars in Figure 4a. We have taken the mean for each planetary rotation, since it is evident from Figure 4a that $|B_\phi|$ varies with System III longitude, and taking instead the mean of each pass through the current sheet edge results in the introduction of a small planetary-period oscillation in values that, while interesting, is not comparable with HST data owing to the limited CML range of Earth-based observations. The mean values obtained are shown by the crosses in Figure 4a, while the fitted cubic spline is shown by the solid line. We now turn to the analysis of these data in terms of the large-scale current system, and compare the currents with the auroral intensities.

3. Analysis

3.1. Magnetospheric Currents

The magnitude of the azimuthal field observed at the northern edge of the current sheet $|B_\phi|$ is related to the radial current via Ampère’s law, which yields
\[ I_{\rho N} = \frac{|B_{\rho N}|}{\mu_0} \]  

where, \( I_{\rho N} \) is the magnitude of the portion of the height-integrated radial current per unit length of azimuth (in A m\(^{-1}\)) that is northward of the \( B_y = 0 \) surface within the current layer (see Figure 1), and \( \mu_0 \) is the permeability of free space. In the case of north-south symmetry, \( I_{\rho N} \) would be equal to half the total height-integrated current per unit length of azimuth \( I_{\varphi} \), but as discussed above this is not necessarily the case. The value of \( I_{\rho N} \) as computed from the cubic spline for \( |B_y| \) is shown by the solid line in Figure 5b. The radial current flowing per radian of azimuth (in A rad\(^{-1}\)), given by

\[ I_{\rho N} = \rho I_{\varphi N} \]  

is then shown by the black line in Figure 5c. It is evident that the values of \( I_{\rho N} \) range between a few MA rad\(^{-1}\) to \(~27\) MA rad\(^{-1}\). For comparison with the auroral intensities, we have obtained the mean of \( I_{\rho N} \) as computed from the cubic splines, within 5 h windows centered on the times of the HST observations (corrected for one-way light travel time between Jupiter and Earth). These values are shown by the circles in Figure 5c. Errors on these and below measurements are computed from the standard deviation of the selected data points within the 5 h windows and propagated using standard formulae. Such broad intervals are chosen owing to, first, the fact that the HST observation times are ~0–2 h different to the points that determine the cubic spline, and second, a lack of information regarding the response time between events in the magnetosphere and the ionosphere, but which is likely to be on the order of tens of minutes to a few hours based on Alfvén wave propagation timescales. It is worth highlighting at this stage the clear apparent relation between the \( I_{\rho N} \) values and the maximum auroral intensities \( I_{\text{UT max}} \) shown in Figure 5d.

While the radial current provides an important measure of the strength of the M-I coupling current system, discrete auroral emission is produced by the kinetic energy flux associated with downward-precipitating electrons carrying upward field-aligned current, given by the divergence of the field-perpendicular current. Under the assumption of approximate local axisymmetry, that is, scales of variation in latitude in the ionosphere are much shorter than scales of variation in longitude, we take for the field-aligned current density flowing out of the northern ionosphere (and into the northern face of the current sheet)

\[ j_{B N} = \frac{2 B_J}{\rho |B_{\varphi N}|} \frac{dI_{\varphi N}}{d\rho} \]  

where, \( B_J \) is the JRM09 dipole equatorial surface field strength of 417,000 nT and \( |B_{\varphi N}| \) is the modulus of the north-south field threading the equatorial plane. The field-aligned current is dependent on the radial profile of the radial current at any given time. Though we have plotted the observations versus radial distance \( r \) in Figure 5, we are assuming that the variations observed by this single spacecraft indicate temporal, rather than spatial, changes. Though with one spacecraft we cannot be entirely sure that this is the case and not a result of small scale features associated with, flux tube interchange, we note that flux tube interchange and outward transport of angular momentum is directly associated with the M-I coupling current system, and, as shown in Section 3.2 below, the co-variation with the temporal changes in the auroral intensity indicates the variation in \( |B_y| \) is also largely temporal.

Under this assumption, it is necessary to estimate the spatial profile of the radial current per radian of azimuth using a model, and for this purpose we use a simple empirical profile of the radial current per radian inspired by the “Non-enhancement” M-I coupling/magnetodisc modeling results of Nichols et al. (2020), which was produced for Orbit 11 data. Hence, though it is not included in the statistical analysis in Section 3.2 below due to the LT range considered, we show in Figure 6a the Orbit 11 \( |B_y| \) data along with the N20 modeled profile in red to illustrate the link between the magnitude of the radial current per radian and the auroral intensity. Note the modeled \( |B_y| \) profile here is not latitude corrected (unlike in Nichols et al., 2020’s Figure 2), in order to compare with the data at the edge of the current sheet. N20’s modeled \( I_{\rho N} \) profile, shown in red in Figure 6b, increases sharply in the inner region inside of \(~27\) R\(_{J}\), and is largely flat thereafter. The profile broadly agrees with the \( I_{\rho N} \) profile computed from the \( |B_y| \) outside of the disturbed interval over the radial range \(~40–55\) R\(_{J}\). To estimate the field-aligned current required to feed the observed radial current at each point of HST observation, we have
produced an empirical formulation for the radial variation of $I_{\rho N}$ that is closely similar to N20's model profile, and is given by

$$I_{\rho N} = \frac{9}{2} \left( \frac{\tanh[\rho / R_J] - 24}{6} + 1 \right) \text{ MA rad}^{-1}.$$  \hspace{1cm} (4)

This profile is shown by the blue dotted line in Figure 6b. We have then scaled this empirical $I_{\rho N}$ profile to match each value of $I_{\rho N}$ measured at the points of HST observations. It is important to note then that in this study we have not solved the Hill-Pontius equation (Cowley et al., 2002; Hill, 1979; Nichols & Cowley, 2004) or computed a new magnetodisc solution (Nichols et al., 2015) for each HST data point. We make no assumptions about the timescales for the maintenance of force balance. These scaled $I_{\rho N}$ profiles are not an output of a steady state model of radial force balance and M-I coupling, but simply provide an estimate of the geometry of the field-aligned current from which an estimate of the field-aligned current density can be made, given the observed radial current per radian. Three examples of these scaled profiles are shown in Figure 5 by the gray lines, scaled to meet those points that are encircled, and also the two cases for the HST observations in Orbit 11 are shown in Figure 6b. We have limited the radial range of current measurements in this study to distances greater than 27 $R_J$, since inward of this distance the empirical profile rises very sharply from small values, and the overall amplitude of the current inferred is highly sensitive to small changes in the observed values of $I_{\rho N}$, such that this process becomes unreliable. Having said this, extending the limit into 20 $R_J$ includes only 1 more visit, which only changes the resulting correlation coefficients in the second decimal place.
Once the empirical \( I_{\rho\rho} \) profiles have been determined, the field-aligned current density mapped to the ionosphere \( j_\parallel \) is computed using Equation 3, evidently proportional to \( I_{\rho\rho} \) at a given distance, and the maximum value is taken for comparison with the peak auroral intensities as discussed above. Two examples for Orbit 11 are shown in Figure 6c. To estimate the peak precipitating electron energy flux, we use the theory of Knight (1973), which is consistent with Juno observations of the accelerated electron population above Jupiter’s auroral region (Clark et al., 2018). The precipitating energy flux is given by

\[
E_f = \frac{E_{f0}}{2} \left[ \left( \frac{j_{\rho\rho}}{j_{\parallel 0}} \right)^2 + 1 \right],
\]

where, \( j_{\parallel 0} \) is the maximum field-aligned current that can be carried by unaccelerated magnetospheric electrons, given by

\[
j_{\parallel 0} = eN \left( \frac{W_{th}}{2\pi m_e} \right)^{1/2},
\]

with a corresponding precipitating energy flux \( E_{f0} \) of

\[
E_{f0} = 2N W_{th} \left( \frac{W_{th}}{2\pi m_e} \right)^{1/2},
\]

where, \( e \) and \( m_e \) are the electron charge and mass, respectively, and \( N \) and \( W_{th} \) are the high latitude electron number density and thermal energy, respectively. With Clark et al. (2018) we take \( N = 0.018 \) cm\(^{-3}\) and \( W_{th} = 2.5 \) keV. The resulting peak precipitating electron energy fluxes \( E_{f\text{max}} \) for the Orbit 11 example are shown in Figure 6d, in which the we also show on the right hand axis the conversion to auroral intensity assuming the “canonical” conversion efficiency, 1 mW m\(^{-2}\) of precipitating electron energy flux leads to 10 kR of H\( \alpha \) emission. Note that this value is based on the ~9–11 kR spread of modeling studies (Gérard & Singh, 1982; Grodent et al., 2001; Gustin et al., 2012; Waite et al., 1983). The peak electron energy fluxes are then compared with the peak auroral intensities \( I_{\rho\rho \text{max}} \). The values obtained for the two HST observations on Orbit 11 are shown by the horizontal lines in Figure 6d, which broadly agree with the estimated peak energy fluxes, underlining the results of Nichols et al. (2020). The results of the comparison over the whole data set included in the present study are discussed in Section 3.2 below.

Before discussing the overall results, however, we first briefly present in Figure 7 the results for Orbit 4 in the same format as for Orbit 5. For Orbit 4, it is evident that the values of \( I_{\rho\rho} \) and \( I_{\rho\rho \text{max}} \) are again apparently closely related, as for Orbit 5. HST observations excluded from the main analysis for reasons discussed above are shown in red. Specifically, we have excluded the interval between days 24 and 26 when the spacecraft entered the magnetosheath owing to a solar wind compression, but the bright auroral intensities observed would be consistent with elevated radial current if its magnitude was essentially constant between the similar values either side of the excluded interval. Also excluded are two dawn storm images observed on days 22 and 29. These are discussed further below, but it is worth noting that neither dawn storm occurred during intervals of elevated radial current.

### 3.2. Comparison of Auroral Intensities With M-I Coupling Current Parameters

We now consider the relation of the radial current and inferred peak precipitating electron energy flux to the peak auroral intensities. In Figure 8 we first show plots of the peak mean auroral intensities \( I_{\rho\rho \text{max}} \) versus (a) the radial current per radian of azimuth \( I_{\rho\rho} \) at the point of observation as discussed above, and (b) \( I_{\rho\rho}^2 \). We also show with the solid line and gray region the linear regression and associated 95% confidence interval using weighted least squares fitting to \( I_{\rho\rho}^2 \). We specifically consider here \( I_{\rho\rho}^2 \) rather than \( I_{\rho\rho} \) based on the expectation from Equation 5 that the precipitating energy flux is proportional to the square of the current magnitude, under the assumption that outside ~27 R\( _J \) the \( I_{\rho\rho} \) radial profile is flat, as is broadly suggested by the data and model. The gradient of the linear regression in Figure 8b is ~0.01 ± 0.0005, and the Pearson correlation coefficient \( R \) for \( I_{\rho\rho}^2 \) is ~0.9, with negligible (~10\(^{-13}\)) probability that the two variables are unrelated. The proportion of the variation of the auroral intensities that is explained by changes in the current system parameters is then \( R^2 \approx 81\% \). The linear fit to \( I_{\rho\rho}^2 \) is also shown in Figure 8a, which further highlights the broadly parabolic nature of the relation...
between $I_{UV \max}$ and $I_\rho N$. In Figure 8c we show $I_{UV \max}$ versus the estimated peak electron energy flux $E_{f \max}$, along with the results of a linear regression as for $I_\rho N^2$. The gradient of the linear regression in Figure 8c is $\sim 4.5 \pm 0.4$, implying 1 W m$^{-2}$ of precipitating energy flux is associated with $\sim 4.5$ MR of auroral emission, or equivalently 1 mW m$^{-2}$ is associated with 4.5 kR a factor of $\sim 2$ below the canonical 10 kR in this case. This result is further discussed in Sections 3.3 and 4 below. We have also undertaken a similar analysis using the two

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**Figure 7.** Plot of magnetic field, radial current, Hubble Space Telescope (HST) auroral intensity measurements and Juno position for Orbit 4 in the same format as for Figure 5, except that excluded HST data points in panel (d) when Juno was in the magnetosheath are shown in red, while the dawn storm intervals on either side are shown by the encircled points.

**Figure 8.** Plots of maximum mean auroral intensity $I_{UV \max}$ in MR versus (a) the radial current per radian of azimuth $I_\rho N$ in MA rad$^{-1}$, (b) $I_\rho^2 N^2$ in MA$^2$ rad$^{-2}$ and (c) the estimated peak electron energy flux $E_{f \max}$ in W m$^{-2}$. Also shown in panels (b) and (c) are linear regressions fitted to $I_\rho N^2$ and $E_{f \max}$ in W m$^{-2}$ (solid lines) along with their 95% confidence intervals in gray. The linear fit to $I_\rho N^2$ is also shown in panel (a). The Pearson correlation coefficients $R$ are shown in panels b and c, along with the gradient of the best fit line.
latitude-integrated intensity measurements described in Section 2.1, with correlation coefficients of 0.87 for the integration over a fixed ±1° width and 0.61 for the integration over the FWHM, as shown in Figures S11 and S12 in the Supporting Information S1. For completeness, we also show results including the three images exhibiting dawn storms, which were rejected from the main analysis, in Figure 9. All three dawn storms occurred during intervals of low radial current, lending weight to the idea that such events are related to nightside reconnection and depolarizations, rather than the M-I coupling currents directly.

3.3. Effect of a Partial Ring Current

In the above analysis, the observed radial current was assumed to be fed wholly from the ionosphere via upward field-aligned currents as shown in Figure 1, as would be the case if the current system were exactly axisymmetric. As discussed above, however, at Jupiter the azimuthal current in the equatorial current sheet is stronger on the nightside of the planet than on the dayside, thus forming a PRC system (Bunce & Cowley, 2001; Khurana, 2001; Lorch et al., 2020; Vogt et al., 2017). Continuity may be maintained by radial currents in the current sheet flowing outward at dawn and inward at dusk, and/or by field-aligned currents flowing into the ionosphere at dawn and out of the ionosphere at dusk. In the event that continuity is maintained through a radial current, a component of the observed current would then not relate to the M-I coupling current system, but instead form part of a current flow that closes within the equatorial plane, at least out to the magnetopause, which should in this scenario be subtracted from the observed radial current. On the other hand, if the PRC diverts to field-aligned current, its contribution to the field-aligned current density (downward in the dawn ionosphere) should be subtracted from the inferred upward M-I coupling field-aligned current. The relationship between the radial current and the field-aligned current is thus affected in the same sense in both scenarios (see discussion in Appendix A).

Here, we have used measurements of the radial component of the magnetic field $B_r$, together with an empirically based current sheet model, to estimate the magnitude of the PRC at any time, $i_{RCφ}$, and from its divergence its potential contribution to either the radial current or the field-aligned current density. The details of the method are given in Appendix A, but briefly, we employ data outside the current sheet, identified by a threshold on $\dot{A} \dot{B}_ρ$. 

![Figure 9](image-url) Plots of (a–c) the Hubble Space Telescope images exhibiting dawn storms, excluded from the main analysis, in the same format as in Figure 2, along with (d–f) an equivalent to Figure 8 with the fits including these dawn storm data points, which are highlighted with red encircled points.
apply a latitude correction, and fit cubic splines to mean values for every half-rotation. We show in Figure 10a the modulus of the latitude-corrected radial field $A_{\rho}'$ and the cubic spline fit (solid line) for Orbit 5. We also show with the dashed line the radial field values of the empirical “RBC” model of Bunce et al. (2002), given by Equation A5. We compute the ratio of the spline fit to $A_{\rho}'$ at a given location and the estimated PRC component $i_{\rho,R} \rho$ (dashed line) in mA m$^{-1}$, (c) the measured radial current per unit of azimuth $i_{\rho,N}$ in MA rad$^{-1}$ (solid line) and the residual $\Delta i_{\rho,N}$ after subtraction of the ring current component (dashed line), (d) the peak field-aligned current densities $j_{\|,N}$ max from Equation 3 (circles), the current densities $j_{\|,R}$ from $\nabla \cdot i_{\rho,R}$ (diamonds) and the difference (triangles), (e) the maximum auroral intensity of the dawn-side main emission $I_{\text{UV}}$ max as for Figure 5d, (f) the axial (z) distance from the current sheet as for Figure 5d. In panel (c) we highlight the $\Delta i_{\rho,N}$ values at the time of HST observations and show the associated scaled theoretical profiles in the same format as Figure 5c.

Figure 10. Plot of cylindrical radial magnetic field, radial and field-aligned currents including the effects of the partial ring current (PRC), Hubble Space Telescope (HST) auroral intensity measurements and Juno position versus Juno's radial distance in R$_J$. Specifically, we show (a) the observed values and fits for modulus of the latitude-corrected radial field $|B'_r|$ in the same format as for Figure 5a, along with the values for the RBC partial ring current model from Equation A5 (dashed line), (b) the measured radial current intensity $i_{\rho,N}$ (solid line) and the estimated PRC component $i_{\rho,R} \rho$/2 (dashed line) in mA m$^{-1}$, (c) the measured radial current per unit of azimuth $i_{\rho,N}$ in MA rad$^{-1}$ (solid line) and the residual $\Delta i_{\rho,N}$ after subtraction of the ring current component (dashed line), (d) the peak field-aligned current densities $j_{\|,N}$ max from Equation 3 (circles), the current densities $j_{\|,R}$ from $\nabla \cdot i_{\rho,R}$ (diamonds) and the difference (triangles), (e) the maximum auroral intensity of the dawn-side main emission $I_{\text{UV}}$ max as for Figure 5d, (f) the axial (z) distance from the current sheet as for Figure 5d. In panel (c) we highlight the $\Delta i_{\rho,N}$ values at the time of HST observations and show the associated scaled theoretical profiles in the same format as Figure 5c.
\[ \sim 1-3 \text{ \mu A m}^{-2}, \text{ such that the resultant upward field-aligned current densities } \Delta j_{\parallel}, \text{ shown by the triangles, exhibit similar variations to } j_{\parallel N}^{\text{max}}. \]

Equivalent plots of \( I_{UV}^{\text{max}} \) versus current system parameters for the two cases of the diversion of the azimuthal current discussed above are shown in Figure 11. Specifically, we show the equivalents of Figures 8b and 8c but using \( \Delta j_{\parallel} \) in Figures 11a and 11b, while in Figure 11c we show the equivalent of Figure 8c but using \( \Delta j_{\parallel} \).

Overall, the effect on the correlation is minimal, with essentially the same correlation coefficients \( R \) of \( \sim 0.9 \). The principal change is the increased gradients of the linear regression lines owing to the reduced current intensities. The gradient in Figure 11b is \( \sim 10.6 \pm 1.0 \text{ MR per W m}^{-2} \), consistent with the modeled 9–11 kR per mW m\(^{-2}\) in this case, while that in Figure 8b is \( \sim 5.3 \pm 0.5 \text{ MR per W m}^{-2} \).

### 3.4. Comparison of Auroral Intensities With the Rate of Change of Magnetic Field Energy Density

We finally turn to a comparison of the auroral intensities with the rate of change of magnetic field energy density outside the current sheet. We again employ cubic splines fitted to mean values obtained every half-rotation for this analysis, for the reasons outlined above but also to produce a smoothly varying profile from which to compute the rate of change. The results are shown in Figure 12 versus UT for Orbit 5, as studied by Y19. Similar plots for all orbits considered are available in the Supporting Information S1. Note the interval considered by Y19 is highlighted in light blue. The steps of the algorithm used to determine the rate of change of the magnetic pressure are outlined as follows:

1. We have again selected data points outside the current sheet, here with the conditions \( \dot{B}_{u} < 2.4 \text{ nT h}^{-1} \) and \( \sigma^2 < 0.005 \text{ nT}^2 \) where, \( \sigma^2 \) is the variance of \( B_{u} \) in a rolling window of width five points. These conditions ensure the rate of change calculated is definitely due to temporal variation of the field outside the current sheet, and the selected \( p_{B} \) data points for Orbit 5 are shown in black in Figure 12a.

2. The magnetic pressure exhibits a systematic variation on a time scale of several days due to the spacecraft’s motion through the magnetosphere. To isolate the changes on the time scale of a planetary rotation we have fitted the function \( p_{BL} = a(b/r)^{c} \) (L meaning “low order”) where, \( a \), \( b \), and \( c \) are constants, to the selected data using non-linear least squares. The fit computed for Orbit 5 is shown by the black line in Figure 12a, and the ratio \( \Pi = p_{B}/p_{BL} \) is shown in Figure 12b. The ratio \( \Pi \) retains the temporal variation on the time scale of interest.

3. We have then fitted cubic splines to the mean values of \( \Pi \) every half-rotation, using the same method described for the \( B_{u} \) analysis above. This produces a smoothly varying profile that represents the observed temporal changes in \( \Pi \).

4. The method of fitting points to every half-rotation raises the possibility of introducing an artificial planetary-period oscillation in values. In order to remove any such variation, we filtered the cubic spline with an Infinite Impulse Response Butterworth bandstop filter centered on the planetary rotation frequency, with the result shown by the solid line in Figure 12b. This smoothly captures the temporal variation in \( \Pi \), and is used to determine its rate of change.
5. To compute the rate of change of the magnetic pressure, we have obtained the numerical derivative of the filtered spline $\dot{\Pi}$, which is shown in Figure 12c. Comparison of $\dot{\Pi}$ with $\dot{p_B}$ and $\Pi$ in Figures 12a and 12b, shows that $\dot{\Pi} < 0$ when the magnetic pressure is dropping, and vice versa, over time scales of a planetary rotation. This can then be directly compared with the auroral intensities shown in Figure 12d, as discussed below.

Y19 highlighted the two HST observations obtained on days 76 and 78 (March 17 and 19), which exhibit elevated main emission intensities relative to the others during this interval, and they pointed to the intervals of decreasing magnetic field magnitude closely following each of these times, as is also evident in our analysis by the intervals of $\dot{\Pi} < 0$ on these days. However, it is worth noting that there is also an interval of $\dot{\Pi} < 0$ at the time of an HST observation on day 81 (March 22), outside of the interval considered by Y19, but which does not correspond to high auroral intensities.

We show in Figure 13 plots of the peak mean auroral intensity versus $\dot{\Pi}$ in a manner similar to the analysis for $B_\phi$ shown in Section 3.1. Since, Y19 pointed to intervals of declining field strength following the two observations of bright auroras, we have plotted the results for the mean values of $\dot{\Pi}$ in (a) 5 h windows centered on each HST observation, (b) 5 h windows following each HST observation and (c) 10 h windows following each HST observation. The Pearson correlation coefficient $R$, computed using weighted least squares, is shown in each panel of Figure 13, all of which are very low. Note that we have repeated this analysis including the dawn storm images, and the magnitudes of the correlation coefficients are similar. We have also repeated the analysis using the integrated brightness measurements, with the results shown in Figures S13 and S14 in the Supporting Information S1. The correlation coefficient magnitudes range over $0.11 \leq R \leq 0.33$, with the maximum correlation magnitude found for the intensity integrated over the FWHM and the 5 h windows following each HST observation. Overall, there

**Figure 12.** Plot showing (a) the magnetic pressure $p_B$ in nPa (selected data points in black, others in gray) along with the fit to the selected data $p_{BL}$ (solid line), (b) the ratio $\Pi = p_B/p_{BL}$ along with a filtered cubic spline (solid line), (c) the numerical derivative of the cubic spline $\dot{\Pi}$ in h$^{-1}$, (d) the axial distance of Juno from the current sheet in the same format as Figure 5, and (e) the maximum auroral intensity. The interval shown in blue is that considered by Y19 (their Figure 2). The gray region in panel (d) shows $z_{CS} = \pm 3 R_J$. 

5. To compute the rate of change of the magnetic pressure, we have obtained the numerical derivative of the filtered spline $\dot{\Pi}$, which is shown in Figure 12c. Comparison of $\dot{\Pi}$ with $\dot{p_B}$ and $\dot{\Pi}$ in Figures 12a and 12b, shows that $\dot{\Pi} < 0$ when the magnetic pressure is dropping, and vice versa, over time scales of a planetary rotation. This can then be directly compared with the auroral intensities shown in Figure 12d, as discussed below.
is no evidence of an association between the auroral intensity and intervals of $\dot{\Pi} < 0$, with only two or three outliers in the delayed windows following the expectation of the “magnetic loading/unloading” scenario. It is, however, worth noting that both dawn storms in Orbit 4 occurred near or during intervals of slightly reduced magnetic pressure lasting around a planetary rotation, as shown in Figure 14. The case for the third dawn storm in Orbit 6 (not shown for brevity but can be seen in Figure S9 in the Supporting Information S1) is less clear but possibly consistent.

Figure 13. Plots of maximum mean auroral intensity $I_{UV,\text{max}}$ in MR versus $\dot{\Pi}$ in nPa h$^{-1}$ in the same format as Figure 8, for (a) 5 h windows centered on each Hubble Space Telescope (HST) observation, (b) 5 h windows following each HST observation and (c) 10 h windows following each HST observation.

Figure 14. As Figure 12 but for Orbit 4. The points for the dawn storms are encircled.
4. Discussion

We have shown that there is a significant correlation with \( R \approx 0.9 \) between the peak intensity of Jupiter’s northern dawnside main auroral emission and the square of the observed radial current per radian of azimuth observed in the north on the dawn side, the \( J \times B \) force of which accelerates magnetospheric plasma in the sense of corotation. This strong correlation indicates that \( \sim 81\% \) of the variation in auroral intensity is associated with changes in the current magnitude, and the chance that the two phenomena are unrelated is negligible. Hence, the probability that the variation in \( B \cdot J \) is in fact due to small scale features that by chance produce an apparent temporal variation that is unrelated to that observed in the auroral emission is exceedingly small. We have also scaled an empirical radial profile of the radial current per radian to observations, and shown that there is a similar correlation with the estimated peak precipitating energy flux at each point of observation. These are consistent with theoretical expectations for auroral emission driven by magnetosphere-ionosphere coupling currents. Specifically, modeling studies indicate Jupiter’s FUV auroral intensity is proportional to the precipitating electron energy flux, which, from Knight (1973)’s theory, is proportional to the square of the upward field-aligned current density. This upward field-aligned current flows from the planet into a thin equatorial sheet of radial current (see Figure 1). If the latitudinal spatial scale of the field-aligned current is invariant, then any observed changes in the total radial current per radian flowing in the current sheet correspond to similar variations in the field-aligned current density. Hence, the auroral intensity is expected to vary with the square of the total radial current per radian, as we have found. The computation of the peak precipitating energy flux \( E_{f, \text{max}} \) depends on an empirical radial profile of the radial current per radian, which is broadly flat outside of \( \sim 27 \text{ R}_J \). The similarity of the correlation of the auroral intensity directly with the observed \( I_{\text{prec}}^2 \) (at all radial distances considered) with that found for \( E_{f, \text{max}} \) is consistent with an essentially flat profile for \( I_{\text{prec}} \) beyond \( \sim 27 \text{ R}_J \). Note we also considered measures of the intensity integrated over the latitudinal intensity profiles, using both a fixed \( \pm 1° \) width relative to the emission peak and the FWHM. We found that the former exhibits a similar correlation to the peak intensity, while the latter has a reduced correlation of \( R \approx 0.6 \). The reduced value for the latter lends support to the assumption that the radial extent of the field-aligned currents is largely constant, implying a different source for the wider (typically lower latitude) emission.

We have further modeled and subtracted a time-variable contribution to the current system arising from the PRC at Jupiter, which has a sink at dawn, and from current continuity must therefore contribute to either the radial or field-aligned currents considered (or possibly some combination of both). In either case, however, this does not reduce the correlation significantly. The principal effect is to increase the gradient of the linear fit between the auroral intensity and precipitating electron energy flux, which in our results implies \( 1 \text{ mW m}^{-2} \) of precipitating electron energy flux is associated with 5–11 kR of \( \text{H}_2 \) auroral emission. This is consistent with the 9–11 kR of modeling studies (Gérard & Singh, 1982; Grodent et al., 2001; Waite et al., 1983). A possible origin of the slight discrepancy at the lower end could arise from the assumed profile of the radial current, which may increase somewhat more slowly in the inner region than in the empirical model employed here. This should be examined in future studies. Overall, these results demonstrate a direct connection between the M-I coupling current system associated with corotation enforcement and the main auroral oval, at least on the dawn side, in conformity with the prior discussions of Hill (2001), Southwood and Kivelson (2001) and Cowley and Bunce (2001), and contrary to the conclusions of Bonfond et al. (2020).

As discussed in the Introduction, a key surprise of the Juno mission has been the relative lack of downward precipitating electron energy flux associated with inverted-V structures, and instead the prevalence of bi-directional electron beams, broadband (stochastic) electron acceleration, and kinetic Alfvén wave activity above the auroral zones of Jupiter (e.g., Gershman et al., 2019; Mauk et al., 2020). Such observations have been taken as evidence against the association of Jupiter’s main auroral emission with magnetosphere-ionosphere coupling currents (Bonfond et al., 2020). However, while here and in previous works we have employed Knight (1973)’s theory to estimate the precipitating electron energy flux associated with the intense field-aligned currents, it would not be surprising if intense waves were also driven in these field-aligned current systems, which scatter and heat the particles. We thus regard the Juno observations as broadly consistent with the existence of a magnetosphere-ionosphere coupling current system, with the primary effect being the field-aligned current, from which the other effects follow. Our work showing explicitly that the dawnside main auroral emission intensity is closely associated with the (net upward) magnetosphere-ionosphere coupling field-aligned currents indicates that this is indeed the case, at least for the dawnside main emission.
While the statistical correlation found here is excellent, there is some remaining variation not explained by observed changes in radial current per radian. This is exemplified by the observations on days 335 and 337 in Orbit 3 (see Figure S1f in the Supporting Information S1), which exhibited significant variation in contiguous HST orbits that is not associated with changes in the radial current measurements. We do note, however, that this is not typical; counter examples are evident in Figures S3f, S4f and S5f in Supporting Information S1, in which the auroral intensity in two adjacent HST orbits are very close to one another, and in general, the timescale for variation of the currents and main auroral emission intensity (dawn storms aside) is of order tens of hours, many planetary rotations. This is much longer than the 0–2h gap between HST observations and selected magnetic field data intervals (which in any case bracket each observation). However, the remaining variation may arise from confounding variables and further physical processes which lead to auroral emission such as wave-particle interactions and diffuse emission from injections as discussed by Bonfond et al. (2020). We thus suggest that such additional components may play a significant additional role in generating the main emission at Jupiter. This is also suggested by the fact that the three dawn storms during the interval occurred during intervals of relatively low radial current, and thus seem to be independent of the M-I coupling current system, perhaps relating to reconnection or dipolarizations on the nightside. We also note that, while our results indicate that the assumption of fixed field-aligned and PRC current system geometries is reasonable, these are likely simplistic, and this should be examined in future studies. Though we have limited our investigation to an interval when it is reasonable to compare dawn-side main emission with Juno’s in situ measurements, there may still be a LT disparity between the two sets of observations. This is increasingly likely as Juno progressed around to the night side, where the in situ observations may increasingly be governed by nightside dynamics, and could be somewhat different from the 3 to 6 h LT sector analyzed here. We reiterate that our analysis does only consider the dawnside main emission, and as such it is presently unclear whether the main emission at other local times is similarly related to the magnetosphere-ionosphere coupling currents. Other auroral forms such as poleward dusk arcs (Nichols, Clarke, Gérard, Grodent, & Hansen, 2009; Prangé et al., 1998), polar auroral filaments (Nichols, Clarke, Gérard, & Grodent, 2009), and swirl and active region emissions (Grodent, Clarke, Waite, et al., 2003; Nichols, Badman, et al., 2017) are also not covered here.

We also note that we have not discussed the physical origin of the variability presented here, which is beyond the scope of the present study. However, a few comments are in order. Many authors have considered the effect of solar wind variability on Jupiter’s magnetosphere and auroras (e.g., Chané et al., 2017; Cowley & Bunce, 2001, 2003; Cowley et al., 2007; Delamere & Bagenal, 2010; Gong, 2005; Southwood & Kivelson, 2001; Yates et al., 2012). The basic argument, however, that auroral intensity and solar wind dynamic pressure should be anti-correlated since compression by the solar wind results in higher plasma angular velocities due to conservation of angular momentum, does not appear to be consistent with observations. Note there are caveats to this simple picture, as discussed by a number of the above authors (e.g., Cowley et al., 2007; Gong, 2005), in the context of the non-steady state response to sufficiently rapid compressions, which may in the short term produce brighter emissions than in the quiescent case. Chané et al. (2017) presented 3D magnetohydrodynamic simulation results, in which the radial current densities were increased in the post-midnight sector for a compressed magnetosphere, and Nichols, Badman, et al. (2017) showed that enhanced main emission intensities were observed following solar wind compressions during the Juno approach. Nichols et al. (2020) implicated the solar wind as the cause of the disturbed conditions and enhanced auroral intensities they analyzed for Orbit 11 (not included in the present study due to the LT constraint). The authors discussed solar wind compression-induced tail reconnection similar to that observed at Saturn (Bradley et al., 2020; Bunce et al., 2005), which would influence the mass content of returning flux tubes via dawn. There is evidence that the magnetosphere was compressed during Orbit 4, since Juno exited the magnetosphere at a radial distance of ≈80 R_J, but we discounted the HST observations obtained during this interval through a lack of radial current measurements (though we noted the bright emissions). This event arguably affected the 1–2 HST observations following (e.g., day 26), but of course the dynamic state of the magnetosphere (i.e., compressed or expanding) is unknown, as it is for the rest of the times of interest. We note that the time scale for changes in the UV emissions in the Io torus following impulsive volcanic events is weeks (Yoshikawa et al., 2017), such that few-day intervals of enhanced variability are perhaps more likely to be driven by the solar wind. Clearly, estimates of the state of the interplanetary parameters and Juno observations of the magnetospheric plasma at the times of these HST observations should be examined in future studies, but we have established here that, whatever the origin of the variability, the M-I coupling current system is centrally involved.
We have also demonstrated the lack of an association between the dawnside main auroral emission intensity and the simultaneous rate of change of the magnetic pressure outside of the current sheet, contrary to the “magnetic loading/unloading” picture of Y19. Examples can be found (e.g., from days 27 to 81 in Orbits 4 and 5, respectively), which occurred during intervals of declining magnetic pressure but where the auroral intensity is not noticeably high. However, it remains true that the bright auroras highlighted by Y19 occurred a few hours prior to intervals of declining magnetic pressure, and none of the very bright auroras had a positive mean rate of change of magnetic pressure in the 10 h following observation. We note that intervals of elevated currents typically last a few days, and we suggest then that this observation arises since, if the current is already high, leading to bright auroral emission, it is unlikely to increase further and instead likely to decrease. It is worth noting that the two dawn storms during Orbit 4 occurred during intervals of slightly reduced magnetic pressure, which may be consistent with a picture related to dipolarization, but with only two examples a strong conclusion in this regard is unwarranted. Solar wind compressions might indeed be associated with increased flux transport, but overall there is no clear relation between flux transport as measured by the rate of change of magnetic pressure outside the current sheet and the dawnside main emission intensity. We suggest this should be examined further by comparison with nightside Juno observations.

5. Summary

We have compared Jupiter’s northern dawn-side main auroral emission intensity observed by HST with the simultaneous magnitude of the northern portion of the dawn-side magnetospheric equatorial radial current as observed by Juno during Orbits 3–7. This data set comprises 35 near-simultaneous measurements of the dawn auroral and radial current intensities. We have shown that the auroral intensity and the square of the radial current per radian of azimuth are correlated with \( R \approx 0.9 \), indicating that \( \sim 80\% \) of the variation in auroral intensity is associated with changes in the current magnitude, with the chance that the two phenomena are unrelated being negligible \( (\sim 10^{-15}) \). We showed that taking into account an estimate of the current contribution due to the equatorial PRC has essentially no effect on the correlation. We have also estimated the precipitating electron energy flux during each observation by scaling an empirical profile of the radial current per radian of azimuth, and showed that 1 mW m\(^{-2}\) of precipitating energy flux is associated with \( \sim 5–11 \) kR of auroral emission, consistent with the 9–11 kR from previous modeling studies. This result provides compelling evidence that the M-I coupling current system at Jupiter powers the planet’s main auroral emission, in conformity with the theoretical picture of Hill (2001), Southwood and Kivelson (2001), Cowley and Bunce (2001) and related studies, and in disagreement with the argument by Bonfond et al. (2020) that the two phenomena are unrelated. We further showed that there is no association between the intensity of the main emission with the simultaneous rate of change of the magnetic energy density outside the current sheet, contrary to the “magnetic loading/unloading” picture of Y19. However, the three dawn storms which were observed during the analysis occurred during \( \sim 10 \) h intervals of slightly reduced magnetic pressure and relatively low radial current, indicating that they are not associated with the M-I coupling current system but may be consistent with a picture involving nightside dipolarizations. Overall, these results provide important new insight into the processes that drive Jupiter’s dawn side main auroral emission.

Appendix A: Estimation of the Magnitude of the Radial Component of the Partial Ring Current

The divergence of the azimuthal current in Jupiter’s PRC system was modeled by Bunce et al. (2002) based on Pioneer, Voyager and Galileo data, and here we use their “RBC” model. We consider the effect of two extreme cases for the maintenance of current continuity, it diverts either wholly radially outward at dawn and inward at dusk or it diverts purely field-aligned, that is, toward the planet at dawn and away from the planet in the dusk. We note immediately, however, that either of these cases, or any arbitrary combination of them, yields the same modified relation between the radial current in the equatorial current sheet and the field-aligned current flowing between the current sheet and the ionosphere. Specifically, directly from current continuity we have

\[
I_{\varphi,N,S} = I_{\varphi,N,S} + \frac{1}{2} \frac{\partial I_{\rho}}{\partial \varphi},
\]

(A1)

where, as previously \( I_{\varphi,N,S} \) is the equatorial radial current per radian of azimuth associated with the N and S systems flowing at radius \( \rho \), \( I_{\varphi,N,S} \) is the total field aligned current per radian of azimuth flowing into the equatorial
current sheet between the inner region and the same radial distance, \( I \) is similarly the total equatorial azimuthal current flowing between the inner region and radial distance \( \rho \), and \( \varphi \) is azimuth measured eastward from noon. The factor of a half assumes that the diverted azimuthal current contributes equally to both N and S systems. The azimuthal current derivative is negative on the dawn side of the planet, such that \( I_{\rho N,S} \) becomes less than \( I_{\rho N,S} \) due to the presence of the PRC, while being positive on the dusk side, such that \( I_{\rho N,S} \) is then greater than \( I_{\rho N,S} \). Since due to continuity the same relationship holds between these quantities irrespective of the PRC closure path, we expect similar perturbative effects with the same senses, governed by the azimuthal gradient of the azimuthal current, under any of these conditions.

We first consider in more detail the case in which the PRC closes wholly in the equatorial plane. The equatorial current, under any of these conditions.

\[
\mathbf{j}_{\rho} = -\frac{1}{2} \nabla \cdot \mathbf{i}_{\rho} + \mathbf{B} \times \mathbf{\Phi}_{\rho}.
\]

The radial current per radian of azimuth associated with the M-I coupling current system in this case is

\[
\mathbf{j}_{\rho} = -\frac{1}{2} \nabla \cdot \mathbf{i}_{\rho} + \mathbf{B} \times \mathbf{\Phi}_{\rho}.
\]

\[
B_{\rho} = A \left( \frac{\rho_0}{\rho} \right)^{m(\varphi)}.
\]

Here, we have estimated the strength of this equatorial current system at any given time from the ratio of the cubic spline of the observed radial field \( B'_R \) (see below) to the RBC model values \( B_{\rho} \). Assuming that the geometry of the current system is unchanged, this yields the instantaneous value of \( A \), and hence the instantaneous \( I_{\rho} \), through Equation (A3), along with the azimuthal and radial current intensities at the location of the spacecraft from Equation (A2). The radial current per radian of azimuth associated with \( I_{\rho} \) is then given by

\[
\Delta I_{\rho N} = I_{\rho N} - \frac{\rho I_{\rho}}{2}.
\]

assuming north-south symmetry for the PRC, and the analysis then proceeds with \( \Delta I_{\rho N} \) as described in the main text for \( I_{\rho N} \).

Considering now the other extreme case that the azimuthal current diverges wholly to field-aligned current, we have \( i_{\rho} \) and instead the current density leaving the northern face of the current sheet is

\[
J_{\rho} = -\frac{1}{2} \nabla \cdot \mathbf{i}_{\rho} + \mathbf{B} \times \mathbf{\Phi}_{\rho}.
\]
which is shown in Figure A2d and by the dashed line in Figure A2e for the radial cut at the 4.8 h LT of Orbit 5. The resultant field-aligned current is then

\[ \Delta j_i = j_i + j_{i_{RC}}, \]

(A9)

which is shown by the thick solid line in Figure A2e. The analysis then again proceeds with \( \Delta j_i \) as described in the main text for \( j_i \).

We now discuss the measurements of the cylindrical radial field \( B_{\rho} \), associated with azimuthal current, which are used to estimate the value of \( A \), and hence \( i_{RC} \) and \( \nabla \times i_{RC} \). The treatment of \( B_{\rho} \) is similar to that for \( B_{\phi} \). In common with previous studies (e.g., Bunce et al., 2002) we are interested only in the relatively smoothly varying magnetic field data outside of the current sheet, and hence we employ the same algorithm as for \( p_B \) in Section 3.4, that is, we first take the rolling mean of the \( B_{\rho} \) data with a 60 min window and then smooth with a Hanning window of width 60 min, with the result in a representative interval shown by the dashed line in Figure A3a. We then compute the gradient of the smoothed profile \( \dot{A} B_{\rho} \), shown in Figure A3b, and we then take all intervals for which \( \dot{A} B_{\rho} < 2.4 \text{nT h}^{-1} \) and \( \sigma^2 < 0.005 \text{nT}^2 \), where \( \sigma^2 \) is the variance of \( B_{\rho} \) in a rolling window of width five points. For \( B_{\rho} \) we use both northern and southern excursions. The selected intervals are illustrated by the black points and gray vertical bars in each panel. Away from the current sheet, the radial field exhibits a systematic decrease in magnitude with increasing latitude, and we have applied the “latitude correction” algorithm of Bunce and Cowley (2001), in which the observed field at position \((r, \lambda)\), where \( \lambda \) is jovianentric latitude) is multiplied by a factor which is given by the modeled cylindrical radial field at radial distance \( r \) but at the latitude of the outer edge of the current sheet (taken here to be \( z = 3 R_J \) as above) divided by the modeled radial field at \((r, \lambda)\). For this purpose, we use the “Non-enhancement” magnetodisc model of Nichols et al. (2020), which yielded results consistent with observations out to \( \sim 100 R_J \). The latitude-corrected selected \( A' B_{\rho} \) data are shown in Figure 4c. As for \( B_{\phi} \), we employ cubic splines fitted to the mean of the selected values in each half-rotation, as shown by the crosses joined by the solid line in Figure A3c. The dashed line in Figure A3c shows the values of \( B_{\rho_{RC}} \) given by Equation A5, and the instantaneous values of \( A \) then inferred from the ratio \( B_{\rho} / B_{\rho_{RC}} \) are shown in Figure A3d. The resulting values of \( i_{RC} \) computed using Equations A2 and A3 are shown by the dashed line in Figure 4e, along with the observed values of \( i_{\phi} \).

**Figure A1.** Streamlines of the equatorial current \( I_{RC} \) as given by the “RBC” partial ring current model. The streamlines are indicated by solid lines, and the labels indicate the total amount of current flowing in the current sheet between it and the streamline at radius \( \rho = 14 R_J \) (the innermost black solid line). Streamlines are illustrated at intervals of 10 MA, and the outer edge of the plot is 100 R_J. LT is indicated and Jupiter is shown to scale in the center. After Bunce et al. (2002).
Appendix B: Estimate of the Magnetopause/Tail Current Fringing Field Within Jupiter’s Middle Magnetosphere

Both empirical analyses of magnetic observations within Jupiter’s middle magnetosphere (e.g., Lorch et al., 2020) and related theoretical modeling (e.g., Pensionerov et al., 2021) assume that the magnetic field in Jupiter’s middle magnetosphere is dominated by the sum of the internal field of the planet combined with the field produced by the equatorial current disk (magnetodisc) together with the field-aligned currents that couple it to the ionosphere. It is thus assumed, either explicitly or tacitly, that the field associated with the anti-solar flow of the solar wind past the magnetosphere, that is the field due to the magnetopause/tail current system, is negligible by comparison in this region. In this appendix, we provide an estimate of these fields and show that this is indeed the case. The calculation consists of two steps. In the first we determine an upper limit to the field strength just inside the subsolar dayside magnetopause based on pressure balance. In the second, we use this field to estimate the curl-free fringing field due to the magnetopause/tail current system that is present throughout the nearer-planet magnetosphere, sunward of the tail region, using a simple theoretical model.

To obtain the value of the magnetospheric field just inside the subsolar magnetopause we employ the simple empirical formula derived by (Huddleston et al., 1998) which relates the radial distance of the subsolar magnetopause, \( R_{MP} \), to the dynamic pressure of the upstream solar wind, \( P_{SW} \), that is,

\[
R_{MP} (R_J) = \frac{35.5}{M_{\alpha} S_{SW} (nPa)}
\]

(F1)
where, empirical exponent \( \alpha = 0.22 \). The value of \( P_{SW} \) at Jupiter typically varies over the range between \( \sim 0.025 \) and \( \sim 0.25 \) nPa, with \( R_{MP} \) then varying over the corresponding range between \( \sim 80 \) and \( \sim 50 \) R\(_J\). We also assume that pressure balance at the magnetopause is achieved solely via the magnetic pressure on the magnetospheric side of the boundary, that is, there is no contribution from magnetospheric plasma pressure, thus yielding a value of the magnetospheric field strength \( B_{MP} \) at the boundary given by

\[
P_{SW} = \frac{B_{MP}^2}{2\mu_0} ,
\]

due to the neglect of the contribution of plasma pressure, this value of \( B_{MP} \) has the nature of an upper limit. The direction of the field is approximately in the co-latitudinal direction, or equivalently the \( -Z \) direction, where \([X, Y, Z]\) is a planet-centered Cartesian system in which \( Z \) is directed northward along the magnetic axis, and the \( X-Z \) plane contains the Sun, towards positive \( X \). Substituting Equation B2 into Equation B1 and inverting to find \( B_{MP} \) in terms of \( R_{MP} \) we thus find

\[
B_{MP} (nT) \approx \left( 1.673 \times 10^5 / R_{MP}^6 (R_J) \right) ,
\]

where, exponent \( \beta = 1/0.44 \approx 2.273 \). The value of \( B_{MP} \) thus varies between \( \sim 23 \) nT for a relatively compressed magnetosphere with a subsolar radius of \( \sim 50 \) R\(_J\), and \( \sim 8 \) nT for a relatively expanded magnetosphere with a

Figure A3. Plot showing Juno MAG measurements of the magnetic field, partial ring current (PRC) parameters, and the spacecraft height above the current sheet versus radial distance in R\(_J\). Specifically, we show (a) the modulus of the cylindrical radial field \( |B_\rho| \) in nT, (b) the gradient \( B_\rho \) in nT h\(^{-1}\), (c) the latitude corrected cylindrical radial field \( |B'_\rho| \), (d) the instantaneous value of \( A \) in nT inferred from the radial field, (e) the radial current intensity in mA m\(^{-1}\) as observed (\( i_{\rho N} \), solid line) and as estimated for the PRC (\( i_{\rho RC}/2 \), dashed line), and (f) the axial \( (z) \) distance from the Khurana (1992) current sheet. The selected data in panel (a) are shown in black, with the rest of the data shown in gray. The vertical gray lines in every panel indicate the locations of the selected data. The average magnetic field values are shown by the crosses in panel (c), and the solid line joining the crosses shows the cubic splines fitted to the average values. The dashed line in panel (c) shows the values given by the RBC empirical model (Equation A5). The dotted line in panel (b) shows the threshold 2.4 nT h\(^{-1}\), while that in panel (d) shows the reference value of \( A = 59.7 \) nT. The horizontal gray bar in panel (f) shows \( |z_{CS}| < 3R_j \).
subsolarm radius of ~80 $R_J$. This field consists of contributions from both the planetary and magnetodisc current sources inside the magnetosphere, and the field due to the magnetopause current itself. These contributions are taken to be approximately equal in magnitude at the boundary (c.f. the Chapman-Ferraro magnetopause problem), such that the field due to the magnetopause current itself in the vicinity of the subsolar magnetopause boundary is taken to be half that given by Equation B3, that is,

$$B_{MP}^* (nT) \approx \left( 8.363 \times 10^4 / R_{MP}^3 (R_J) \right).$$  \hspace{1cm} (B4)

We then apply this value to a simple model of the curl-free (and divergence-free) fringing field throughout the magnetosphere, sunward of the tail system, based on the modeling studies of Alexeev and Feldstein (2001) and Alexeev and Belenkaya (2005), which has also been employed in ring current field modeling at Saturn by both Kellett et al. (2009) and Provan et al. (2021). The Z component of the fringing field is taken to vary linearly with $X$ from the negative value given by Equation B4 at the subsolar magnetopause to positive values on the nightside associated with the fringing field of the tail current system, that is,

$$B_Z^*(X) = -B_{MP}^* \frac{(X - X_0)}{(R_{MP} - X_0)},$$  \hspace{1cm} (B5)

where, $X_0$ is the value of $X$ where $B_z^*$ changes sign. The associated field in the $X$ direction which is such that the overall fringing field is curl-free is then

$$B_X^*(Z) = -B_{MP}^* \frac{Z}{(R_{MP} - X_0)},$$  \hspace{1cm} (B6)

assumed to be zero on the magnetic equator $Z = 0$. The $Y$ component of the field is zero. The field lines of this system thus lie in the $X - Z$ plane, forming rectangular hyperbolae about the center of this system at $[X_0, 0]$. The strength of the fringing field increases linearly with radial distance from zero at the system center $[X_0, 0]$ to $B_{MP}^*$ at radial distance $(R_{MP} - X_0)$, mapping to the subsolar magnetopause in the dayside equator.

The fields in Equations B5 and B6 thus consist of a uniform field in the $Z$ direction, together with a $Z$ field varying linearly as $X$, and an $X$ field varying linearly as $Z$ with the same gradient. These correspond to the leading terms in the series expansion in Equation 2 of Alexeev and Belenkaya (2005) describing the field due to the magnetopause current that shields the planetary and magnetodisc fields. The relative magnitude of the uniform field and the varying term in the $Z$ component for this current system is such that $X_0 = -R_{MP}$ to this order of approximation the negative $Z$ field on the dayside increases in value away from the subsolar magnetopause toward zero at a radial distance on the nightside equal to the subsolar radius on the dayside. We also note that inclusion of higher order terms yields only a weak variation of the fields related to the magnetopause current in the dawn-dusk ($Y$) direction, such that the approximate forms used here are adequate to the present discussion.

The fringing field of the tail current system then adds a positive $Z$ component in the middle magnetosphere region, decreasing towards the dayside, which has the effect of moving $X_0$ towards the planet. In a recent study of Saturn’s ring current field, Provan et al. (2021) found best-fit solutions to Cassini field data typically with $X_0 \approx -(R_{MP}/2)$, such that using this empirical estimate we have

$$B_Z^* (X) \approx -\frac{2}{3} B_{MP}^* \left( \frac{X}{R_{MP}} + \frac{1}{2} \right),$$  \hspace{1cm} (B7)

and

$$B_X^* (Z) \approx -\frac{2}{3} B_{MP}^* \frac{Z}{R_{MP}}.$$  \hspace{1cm} (B8)

we note, however, that our results and conclusions are not sensitively dependent on any reasonably chosen value of $X_0$. The azimuthal component associated with the magnetopause/tail field system is then given by $B_\phi^* = -B_\phi^* \sin \phi$, where $\phi$ is azimuth measured from noon in the sense of planetary rotation. From Equations B5 to B8 we thus have
\[ B_\phi^* (\text{nT}) \approx (5.575 \times 10^4 / R_{\text{MP}}^3 (R_J)) \ Z (R_J) \ \sin \phi , \]  

where, exponent \( \gamma = 1.44/0.44 \approx 3.273 \), and we again note that (in magnitude) this expression has the nature of an upper limit. We also note that, as expected, this azimuthal field has the same sense as the sweepback field produced by plasma subcorotation and magnetosphere-ionosphere coupling on the dawn side of the planet where \( \sin \phi \) is negative, such that \( B_\phi^* \propto -Z \), while having the opposite sense to the sweepback field on the dusk side of the planet where \( \sin \phi \) is positive, such that \( B_\phi^* \propto Z \). The azimuthal component switches sense across the noon-midnight meridian where \( \sin \phi \) is zero. Considering the magnitude of the field on the dawn-dusk meridian where the azimuthal fringing field at given \( Z \) maximizes, together with a magnitude of \( |Z| \approx \pm 5 \ R_J \), employing this study, yields an upper limit of \( |B_\phi^*| \approx 0.78 \ \text{nT} \) for a relatively compressed magnetosphere with \( R_{\text{MP}} = 50 \ R_J \), falling slightly faster than the inverse cube of the magnetopause radial distance to an upper limit of \( |B_\phi^*| \approx 0.16 \ \text{nT} \) for a relatively expanded magnetosphere with \( R_{\text{MP}} = 80 \ R_J \). For a central subsolar magnetopause value of \( R_{\text{MP}} = 65 \ R_J \), the upper limit is \( |B_\phi^*| \approx 0.33 \ \text{nT} \). Such values, typically a few tenths of a nT, are thus generally an order of magnitude smaller than the observed middle magnetosphere azimuthal fields typically >5 nT employed in this study. Our analysis thus indicates that the observed residual fields in the middle magnetosphere, planetary field removed, are principally those of the magnetodisc current sheet and associated field-aligned currents, hence justifying the neglect of consideration of the contribution of magnetopause/tail fields in this and other related studies.

**Data Availability Statement**

These HST data are available at the MAST Archive (http://archive.stsci.edu/hst/search.php), and can be accessed via the doi 10.17909/t9-69wa-4q90. Juno MAG data are from the JNO-J-3-MAG-CAL-V1.0 data set archived at https://pds.nasa.gov.

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