Variation in Pedersen Conductance near Jupiter's Main Emission Aurora: Comparison of Hubble Space Telescope and Galileo Measurements

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Abstract

We present the first large-scale statistical survey of the Jovian main emission (ME) to map auroral properties from their ionospheric locations out into the equatorial plane of the magnetosphere, where they are compared directly to in-situ spacecraft measurements. We use magnetosphere-ionosphere (MI) coupling theory to calculate currents from the auroral brightness as measured with the Hubble Space Telescope and from plasma flow speeds measured in-situ with the Galileo spacecraft. The effective Pedersen conductance of the ionosphere (Σ_P^*) remains a free parameter in this comparison. We first show that the field-aligned currents per radian of azimuth calculated from the auroral observations, found to be $I_{||} = 9.54^{+11.5}_{-0.35}$ MA rad⁻¹ and $I_{||} = 10.64^{+11.1}_{-0.06}$ MA rad⁻¹ in the north and south, respectively, are consistent with previous results. Then, we calculate the Pedersen conductance from the combined datasets, and find it ranges from $0.02 < \Sigma_P^* < 2.26$ mho overall with averages of $0.14^{+0.31}_{-0.08}$ mho in the north and $0.14^{+0.26}_{-0.09}$ mho in the south. Taking the currents and effective Pedersen conductance together, we find that the average ME intensity and plasma flow speed in the middle magnetosphere (10-30 R_J) R_J) are broadly consistent with one another under MI coupling theory. We find evidence for peaks in the distribution of Σ_P^* near 7, 12, and 14 hours magnetic local time (MLT). This variation in Pedersen conductance with MLT may indicate the importance of conductance in modulating MLT- and local-time-asymmetries in the ME, including the apparent subcorotation of some auroral features within the ME.

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Key Points:

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10	• The effective ionospheric Pedersen conductance in Jupiter's main emission auro-
11	ral region is derived from remote and in-situ measurements.
12	• Effective Pedersen conductances of ~ 0.14 mho and field-aligned auroral currents
13	near $\sim 10 \text{ MA rad}^{-1}$ are derived, consistent with past work.
14	• The effective Pedersen conductance varies significantly in magnetic local time, and
15	may explain the enigmatic motions of some auroral forms.

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16 Abstract

We present the first large-scale statistical survey of the Jovian main emission (ME) to 17 map auroral properties from their ionospheric locations out into the equatorial plane of 18 the magnetosphere, where they are compared directly to in-situ spacecraft measurements. 19 We use magnetosphere-ionosphere (MI) coupling theory to calculate currents from the 20 auroral brightness as measured with the Hubble Space Telescope and from plasma flow 21 speeds measured in-situ with the *Galileo* spacecraft. The effective Pedersen conductance 22 of the ionosphere (Σ_P^*) remains a free parameter in this comparison. We calculate the 23 Pedersen conductance from the combined datasets, and find it ranges from $0.03 < \Sigma_P^* <$ 24 2.40 mho overall with averages of $0.13^{+0.26}_{-0.07}$ mho in the north and $0.16^{+0.34}_{-0.10}$ mho in the south. Considering the HST-derived field-aligned currents per radian of azimuth only, we find values of $I_{||} = 9.34^{+5.72}_{-3.54}$ MA rad⁻¹ and $I_{||} = 8.61^{+6.77}_{-3.05}$ MA rad⁻¹ in the north 25 26 27 and south, respectively, in general agreement with previous results. Taking the currents 28 and effective Pedersen conductance together, we find that the average ME intensity and 29 plasma flow speed in the middle magnetosphere (10-30 R_J) are broadly consistent with 30 one another under MI coupling theory. We find evidence for peaks in the distribution 31 of Σ_P^* near dawn, then again near 12 and 14 hours magnetic local time (MLT). This vari-32 ation in Pedersen conductance with MLT may indicate the importance of conductance 33 in modulating MLT- and local-time-asymmetries in the ME, including the apparent sub-34 corotation of some auroral features within the ME. 35

³⁶ Plain Language Summary

The brightest part of Jupiter's aurorae- the main emission- forms arcs of sheet-37 like lights surrounding both magnetic poles, similar to the Earth's aurorae. At both plan-38 ets, these lights are caused by charged particles flowing into the planet's atmosphere, where 39 they collide with gases and glow. According to one theory, at Jupiter these particles are 40 electrons which flow in electrical currents connecting the planet to the charged-particle-41 filled space surrounding it. Here, we use Hubble Space Telescope images of Jupiter's au-42 rorae spanning a decade to build up an average picture of the brightness and location 43 of this main emission. The brightness is related to the energy of the electrons, which in 44 turn is related to the strength of the electrical currents. We then use particle measure-45 ments made by the Galileo spacecraft in orbit around Jupiter to make an average pic-46 ture of these particles as they move around Jupiter. These speeds are related to the same 47 electrical currents, but include an electrical conductivity term describing how easily cur-48 rents flow through Jupiter's auroral atmosphere. We combine all these measurements 49 to calculate the conductivity, and present results which are consistent with expectations 50 but which fluctuate more quickly than expected in parts of the main emission. 51

52 1 Introduction

Jupiter's ultraviolet (UV) auroral main emission (ME), typically the most power-53 ful component of the planet's large-scale auroral regions, takes the form of a partially-54 closed oval of auroral emission surrounding each of the planet's magnetic poles. The Jo-55 vian aurorae are detectable at all local times (LT) including on the planet's dayside (Clarke 56 et al., 2004; Bonfond et al., 2017), where they are significantly brighter than the reflected 57 solar UV at Jupiter (Gustin et al., 2012) and can thus be observed routinely with the 58 Hubble Space Telescope (HST). In the southern hemisphere, the ME forms a nearly cir-59 cular curtain of light; however, the presence of multiple significant non-dipolar magnetic 60 field components in the northern hemisphere complicates the ME structure, resulting in 61 a characteristic 'kidney bean' shape offset from the rotational pole (Grodent et al., 2008; 62 Connerney et al., 2022), as shown by the HST observation and statistically-averaged ref-63 erence main oval ('statistical main oval', or SMO, from Nichols et al. (2009)) in Figure 64 1a. 65

The ME has historically been thought to originate from the magnetosphere-ionosphere 66 (MI) coupling currents flowing in the Jovian middle magnetosphere, radially outward in 67 the equatorial plasma disc, equatorward in the ionosphere, and along magnetic field lines 68 between (Hill, 2001; Cowley & Bunce, 2001; Nichols & Cowley, 2003, 2004, 2005; Ray et al., 2010, 2014; Smith & Aylward, 2009; Tao et al., 2009). This current system arises 70 from the azimuthal distortion (or 'bendback') of the field resulting from the planet's reser-71 voir of angular momentum opposing the decrease in angular velocity experienced by plasma-72 laden flux tubes as they diffuse radially outward. In the absence of torques, these dif-73 fusing flux tubes would tend to conserve angular momentum, resulting in a decrease in 74 the angular velocity proportional to r^{-2} . As the flux tubes lag behind corotation, they 75 warp the magnetic field resulting in the azimuthal bendback of the field structureThe 76 azimuthal component of the magnetic field now present results in a loop of field-aligned 77 current which acts to partially enforce the corotation of the plasma within the magne-78 todisk by exerting a $\mathbf{J} \times \mathbf{B}$ force in the direction of corotation. The strongest field-aligned 79 currents occur near where rigid corotation breaks down (Hill, 1979; Nichols & Cowley, 80 2004). The ME current system is characterized primarily by the rapid rotation and strength 81 of Jupiter's magnetic field, rather than by solar influence as is the case in the Earth's 82 own magnetosphere and auroral ovals (Cowley & Bunce, 2001; Southwood & Kivelson, 83 2001), though solar wind influence is not completely absent (Kita et al., 2019; Nichols 84 85 et al., 2017). These MI-coupling currents and the associated ME ovals are thus always present, owing to the continuous production of Iogenic plasma and diffusion of this plasma 86 outward through the magnetosphere. 87

The production and diffusion of Iogenic plasma is not constant and the Jovian mag-88 netosphere varies in System III (SIII) magnetic longitude (λ_{III}) , local time (LT), and 89 magnetic local time (MLT). This results in various asymmetries in the brightness, shape, 90 distribution, and dynamics of auroral forms within the ME oval. While both hemispheres 91 have similar total emitted UV powers, the southern ME is brighter on average than the 92 northern (Gérard et al., 2013) and the dusk side of the ME is brighter on average than 93 dawn, an effect which is amplified in the brighter southern hemisphere (Bonfond et al., 94 2015). On occasions where the dawn side is brighter than dusk, an exceptionally bright 95 auroral feature- a dawn storm, perhaps- is typically located on the dawn ME (Gérard, 96 Grodent, et al., 1994; Bonfond et al., 2021; Rutala et al., 2022). While the locations of 97 the ME remain fixed in SIII longitude and latitude (Clarke et al., 2004; Gérard, Dols, 98 et al., 1994; Grodent et al., 2003), auroral features on the ME may subcorotate, lagging 99 behind the rigid corotation rate of the planet. Subcorotation occurs more often in the 100 dawn sector than the noon and dusk sectors (Rutala et al., 2022), an effect which ap-101 pears to be separate from the appearance of bright dawn storms. Additional subcoro-102 tating auroral forms, the ME auroral discontinuity (Radioti et al., 2008) and small-scale 103 brightening (Palmaerts et al., 2014) are observed localized near noon. The dusk side of 104 the ME as viewed from the Earth is typically wider and more diffuse than near dawn 105 (Gérard, Dols, et al., 1994); this asymmetry is larger in the northern hemisphere, where 106 the northern magnetic anomaly is typically located in remote observations (Grodent et 107 al., 2008). This asymmetry was originally considered to be a variation in local time (Caldwell 108 et al., 1992), before improved HST observations made it appear to be a variation in SIII 109 longitude (Gérard, Dols, et al., 1994). While recent Juno UVS observations of the po-110 lar aurorae have revealed considerable local time control (Greathouse et al., 2021), the 111 relationship of this apparent dawn-dusk asymmetry in the ME to either local time or SIII 112 longitude remains unclear. 113

These phenomena have generally been thought to arise from deviations from the ideal axisymmetric MI-coupling theory previously discussed. However, predictions of this theory are not always in accordance with observations, raising the possibility that the MI-coupling theory itself only partially describes the generation of the ME oval at Jupiter (Bonfond et al., 2020). Mean field-aligned currents of 58 MA and 24 MA in the southern and northern ME regions, respectively, have been derived from near-planet ($\leq 2R_J$)

Juno magnetometer (MAG) measurements of magnetic field perturbations associated 120 with MI-coupling currents, reflecting the observed north-south brightness asymmetry of 121 the ME ovals (Kotsiaros et al., 2019). These currents appear in primarily longitudinal, 122 though variable, sheets in keeping with the schematic picture of MI coupling theory. An 123 analysis of the same Juno orbits, but focusing on magnetic field perturbations measured 124 along auroral magnetic field lines at larger radial distance $(4 - 16R_{\rm J})$ in the northern 125 hemisphere, agrees that the current structure is extended in longitude and finds larger 126 currents of ~ 34 MA in that hemisphere, somewhat reducing the north-south asymmetry 127 try (Kamran et al., 2022). Further Juno measurements have found that the field lines 128 associated with ME aurorae host precipitating electrons, as required to drive field-aligned 129 currents, along with bi-directional electron distributions (Mauk et al., 2017, 2018), sug-130 gesting that additional auroral emission zones, co-located or nearly co-located with the 131 ME, may be driven by acceleration processes other than field-aligned potentials (Mauk 132 et al., 2020). The measured bi-directional electron distributions may, however, be a sec-133 ondary effect, driven by the flow of intense field-aligned currents (Nichols & Cowley, 2022). 134 The equatorial radial currents derived from Juno magnetometer measurements are highly 135 correlated with simultaneous HST observations of the dawnside ME auroral intensity (Nichols 136 & Cowley, 2022). On large scales and within the middle magnetosphere, the MI-coupling 137 theory still reproduces measurements of current structures (Kotsiaros et al., 2019; Lorch 138 et al., 2020; Wang et al., 2021; Al Saati et al., 2022; Kamran et al., 2022) and observa-139 tions of ME auroral brightness variation, both during short-term enhancements (Nichols 140 et al., 2020) and solar-wind pressure enhancements (Cowley et al., 2008). 141

A further discrepancy between the modeled and observed auroral MI-coupling sys-142 tem at Jupiter lies in the auroral brightness asymmetry across the dayside ME. While 143 the dusk side of the ME oval is typically observed to be brighter than the dawn side (Bonfond 144 et al., 2015), models predict that this asymmetry should be reversed owing to the larger 145 field bend-back in the dawn sector (Ray et al., 2014). Field bend-back is strongly cor-146 related with ME auroral brightness, particularly near dawn (Nichols & Cowley, 2022). 147 Field bend-back is caused by angular plasma flow speeds in the middle magnetosphere 148 slower than the rotation rate of the planet, or subcorotation relative to the planet's ro-149 tation, so in considering only the quasi-steady-state MI coupling current system, an an-150 ticorrelation between the degree of field bend-back and plasma angular velocity is ex-151 pected (Bonfond et al., 2020). A partial ring current, spanning the nightside middle mag-152 netosphere with a source near dusk and a sink near dawn (Walker & Ogino, 2003) may 153 ease this tension if the ring current closes along field-aligned currents, decreasing the ef-154 fective field-aligned currents near dawn and increasing them near dusk (Bonfond et al., 155 2015). On top of this effect, careful consideration is required to relate instantaneous, in-156 situ measurements of plasma velocity to the measurement of magnetic field bend-back 157 in a dynamic region of the magnetosphere such as the dawn sector. The anticorrelation 158 between field bend-back and plasma velocity is only maintained in the quasi-steady-state 159 scenario. If magnetospheric plasma near dawn is rapidly accelerated, the measured plasma 160 velocity may be high despite large degrees of field bend-back, as the plasma and field lines 161 have yet to "catch up" to corotational velocity. This scenario matches observations of 162 both the plasma (Krupp et al., 2001; Bagenal et al., 2016) and the magnetic field (Khurana 163 & Schwarzl, 2005) near dawn. Such a sudden acceleration of the middle magnetospheric 164 plasma may be driven by a sharp increase in the conductance of the MI-coupling circuit, 165 as is the case near the dawn terminator where the previously-unlit ionosphere is re-photoionized 166 by solar extreme ultraviolet (EUV) light (Tao et al., 2010). This scenario has been sug-167 gested to explain the apparent subcorotation of some auroral forms relative relative to 168 the SMO in the dawn sector (Rutala et al., 2022), and will be explored here in more de-169 170 tail.

Here, we present the first large-scale statistical survey of the typical HST-observed
 ME brightness, spanning more than 10 years and 200 cumulative hours of exposure time.
 The ME brightness is mapped from the polar ionosphere out into the magnetospheric

equatorial plane and averaged in bins defined by MLT, equatorial radial distance (ρ_e), 174 and the solar central meridian longitude (solar CML), so that variations relative to MLT 175 and λ_{III} can be differentiated. From these binned values, the associated maximum field-176 aligned current density and total currents under MI-coupling theory are derived. We com-177 pare the derived total currents from this novel analysis of HST observations to litera-178 ture values, finding good agreement in scale. These values are then compared to non-179 contemporaneous in-situ Galileo Plasma Science (PLS) measurements of the plasma flow 180 speed and associated field-aligned current density and total current binned in the same 181 way as the HST observations in order to perform a superposed epoch analysis. Finally, 182 we compare the HST- and *Galileo*- derived currents directly, assuming that they fully 183 describe the large-scale, time-averaged state of the MI-coupling system, to derive a dis-184 tribution of the Pedersen conductance in MLT, ρ_e , and solar CML. The resulting con-185 ductance distribution is additionally mapped back into the ionosphere. We find that the 186 Pedersen conductance peaks in the dawn sector, and varies primarily in MLT, consis-187 tent with controlling the subcorotation of auroral forms in the dawn ME and helping re-188 solve the tension between high degrees of field bend-back and high plasma velocities in 189 the dawn sector. 190

191 **2 Data**

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2.1 Hubble Space Telescope Data

Archival observations of Jupiter's ultraviolet (UV) aurorae made with the Advanced Camera for Surveys Solar Blind Channel (ACS/SBC) and Space Telescope Imaging Spectrograph (STIS) on HST were obtained for this study. These observations comprise more than 200 cumulative hours of exposure, and span 2007 and 2016–2019; this large survey is expected to be representative of the general state of Jupiter's ME aurorae. This set of observations is available via online archive(Rutala, 2022) with further discussion and details available in Rutala et al. (2022) and references therein.



Figure 1. Plots showing multiple views of Jupiter's northern ME on May 22, 2016 beginning at 18:02:46 UTC, as observed with HST STIS. Panel (a) shows a top-down, polar view of the northern ME, with the statistical main oval (SMO) (Nichols et al., 2009) shown (multi-colored points) along with λ_{III} and latitude graticules (yellow lines). Panel (b) shows a labeled keogram, where the observation in (a) is represented in the first (top) row. The values in both (a) and (b) are log-scaled with colors corresponding to the colorbar beneath. Panel (c) depicts the same keogram, but with a limb-brightening correction applied. Panel (d) shows the corrected keogram projected to the magnetospheric equatorial plane as a function of MLT and ρ_e , with the projected SMO corresponding to the first (multi-colored points, with colors marking the equivalent positions as in panel (a)) and final (red dots) exposures shown. The values in both (c) and (d) are log-scaled, with colors corresponding to the separate colorbar beneath.

Time-tagged STIS observations were split into non-overlapping 30s intervals to cre-200 ate images, while the typical ~ 100 s exposures for the ACS observations were unchanged. 201 Images were reduced and projected onto an equirectangular planetocentric grid using the 202 standard procedures in the Boston University HST data reduction pipeline (e.g. Clarke 203 et al., 2009; Nichols & Cowley, 2022; Rutala et al., 2022); the projection from the HST 204 perspective to an equirectangular grid allows the observations to be viewed from any per-205 spective, as illustrated by the reduced observation mapped to an orthographic polar view 206 in Figure 1a. The factors used to convert the observed auroral brightness from counts/s 207 to kR of unabsorbed H and H_2 emission vary with color ratio (Gustin et al., 2012), which 208 can change rapidly on both small and large scales. Here, we estimate an effective range 209 of color ratio values spanning 5-20 in the ME region from visual inspection of Juno ul-210 traviolet spectrograph (UVS)-based maps of the color ratio distribution (Gérard et al., 211 2018, 2020). We adopt a constant color ratio of 12 for converting HST counts/s to kR 212 unabsorbed H_2 emission here; introducing approximate uncertainties in brightness of -23%213 and +11% corresponding to the lower and upper bounds of the color ratio range, respec-214 tively. These uncertainties are comparable to or smaller than the typical variation in au-215 roral brightness observed in the ME as illustrated in Figure A1, and are not propagated 216 through this analysis as a result. Auroral intensities in the ACS/SBC images were fur-217 ther multiplied by a factor of 1.4 for those using the F115LP filter and 1.6 for those us-218 ing the F125LP filter, following recent changes to the SBC absolute flux calibration (Avila 219 et al., 2019). 220

In each reduced image, an ME brightness profile is measured as the mean bright-221 ness of the brightest quartile of emission within $\pm 5^{\circ}$ perpendicular to the SMO, as found 222 by Nichols et al. (2009), in steps along the ME. 300 steps evenly spaced in distance along 223 the SMO with dynamic sizes were found to maximize resolution while preventing over-224 lap between pixels sampled by adjacent steps. The extracted brightness profile is stacked 225 into a keogram for each image within the same HST visit, and aligned such that the lo-226 cation along the SMO is measured horizontally and exposure time is measured vertically. 227 Figure 1b shows a keogram created in part from the observation in Figure 1a, with SIII 228 coordinates, distance along the SMO, and MLT all labeled. Limb-brightening correction 229 factors found as the inverse cosine of the view angle (Grodent et al., 2005) were applied 230 to each keogram, the results of which are demonstrated in Figure 1c. The inverse-cosine 231 correction assumes a greatly simplified plane-parallel geometry for the aurorae– which 232 in reality have a complex, three-dimensional, time-varying structure- and so generally 233 overestimates the limb-brightening effect very near the edge of planet's disk as viewed 234 by HST. Nonetheless, the limb-brightening is corrected for as, without it, the dawn sec-235 tor tends to incorrectly appear as bright as the rest of the ME (Rutala et al., 2022), which 236 is known to not be true statistically (Bonfond et al., 2015) and which would significantly 237 bias the investigation into the variation of the auroral Pedersen conductance with MLT. 238 A more accurate correction factor would be of great use to future auroral studies, par-239 ticularly those utilizing remote observations. The effect of the overestimation is partially 240 countered by removing all parts of the observations within 10° of the limb; the slight re-241 maining effects of the overestimation will be discussed in the Results. The keogram pro-242 duction process is further discussed in Rutala et al. (2022). 243

In each of the 288 keograms, the auroral brightness (I), local time (LT), latitude 244 (ϕ) , System III longitude (λ_{III}) , and the 1σ width $(\delta\theta)$ of the ME were recorded for ev-245 ery pixel. Pixels were then mapped from λ_{III} and ϕ in the ionosphere to magnetic lo-246 cal time (MLT) and radial distance in the equatorial plane of the mangetosphere (ρ_e) 247 using the magnetic flux equivalence mapping of Vogt et al. (2011). The internal mag-248 netic field for the mapping was specified to be the JRM09 magnetic field model (Connerney 249 et al., 2018) which, over the spatial scales relevant here, is very similar to the more re-250 cent JRM33 model (Connerney et al., 2022). Solar CML values for the mapping were 251 found using ephemerides from the NASA NAIF SPICE toolkit (Acton et al., 2018). The 252 angular width of the ME, $\delta\theta$, was mapped to a radial width, $\delta\rho_e$, in the same manner. 253



Figure 2. Two-dimensional distributions of the auroral brightness for both the (a) northern and (b) southern hemispheres, with colors for each MLT- ρ_e bin corresponding to the colorbar to the right. Each distribution is labeled with the range of solar CMLs it spans; solar CML ranges for which there are no observations were excluded. These distributions show significant structure in MLT, ρ_e , and solar CML that varies between the northern and southern hemisphere. Auroral emissions near noon in the northern hemisphere occasionally map beyond the 30 R_J limit of these plots, thus leaving no observations in these distributions; where auroral emissions near noon are measured, they tend to be fainter than either dawn or dusk in both hemispheres. Additionally, the northern hemisphere ME aurorae sampled here tend to be brighter than those in the southern hemisphere.

The observed and mapped parameters were then binned by 1 hour in MLT, 2 R_J in ρ_e , 254 and 24° in solar CML; a typical, 40 minute HST observation of the Jovian aurorae spans 255 $\sim 24^{\circ}$ of longitude as the planet rotates. Values in each bin were calculated as the arith-256 metic mean. Figure 1d shows the auroral brightness of the keogram in Figure 1c binned 257 in MLT and ρ_J , with the projected SMO locations corresponding to the first and last 258 exposures included for reference. As Figure 1d represents a ~ 40 min. observation, it 259 effectively spans a single bin in solar CML and can as such be binned in MLT and ρ_e 260 and displayed completely in two dimensions. Emissions mapping to radial distances less 261 than that of SMO originate at lower latitudes than the SMO, as is the case particularly 262 near dusk in Figure 1. The binned distributions of auroral brightness are shown for the 263 full set of observations used here in Figure 2; to display these distributions, which are 264 binned in three-dimensional, each panel in Figure 2 represents the two-dimensional dis-265 tribution with respect to MLT and ρ_e corresponding to a single solar CML bin. While 266 the distributions in Figure 1d extend out to 70 R_J to show the full extent of the map-267 ping of the SMO in that configuration, those in Figure 201 extend to $30 R_J$ to allow 268 direct comparison to the Galileo/PLS results discussed in the following section. Context 269

for the distributions in Figure 2, in the form of distributions of both the standard deviation and number of observations in each bin, is provided in Figure A1.

2.2 Galileo PLS Measurements

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Plasma parameters used here are derived exclusively from the numerical moments 273 of Galileo/PLS real-time science data as provided by Frank et al. (2023). While the ad-274 dition of more recent plasma data from the Juno/JADE plasma experiment would prove 275 useful in this analysis, the numerical moments, including velocity, for these ion data are 276 not yet publicly available, nor have the experiment's data been cross-calibrated for di-277 rect comparison to Galileo/PLS data. Both of these analyses would be significant con-278 tributions to understanding the Jovian magnetospheric plasma population, but are be-279 yond the scope of the present study. The *Galileo* spacecraft's native Inertial Rotor Co-280 ordinate (IRC) system, a despun coordinate system based on the spacecraft's geometry, 281 is complex (Bagenal et al., 2016) and has not been fully implemented into SPICE (Acton 282 et al., 2018), due in part to the *Galileo* spacecraft heritage predating the SPICE toolkit. 283 SPICE ephemerides for the *Galileo* spacecraft position are available for all 6751 moments; 284 spacecraft pointing information is only available for 4897 of those 6751. So that the full 285 set of moments can be used, the plasma flow speed is estimated as the root-sum-square 286 of all the velocity components, as the azmiuthal component of the plasma velocity is ex-287 pected to be much larger than the radial and polar components. 288

These numerical moments span 31 of *Galileo*'s 34 orbits, and cover a combined 129 days. The plasma parameters span $10R_J \le \rho_e \le 30R_J$ within $\sim 1 - 2R_J$ of the equatorial plane, with larger distances from the equatorial plane corresponding to larger radial distances. These parameters cover all local times and SIII longitudes, with a bias in local time sampling towards dawn and dusk. Figure 3 illustrates the coverage of the numerical moments relative to *Galileo*'s full orbit and shows this bias. Figures 3a and 3b are plotted in the Jupiter-De-Spun-Sun (JSS) reference frame, which is defined to have



Figure 3. Plots illustrating *Galileo* PLS coverage of the magnetosphere. Plot (a) shows all 34 *Galileo* orbits projected into Jupiter's equatorial plane in the Jupiter-Despun-Sun (JSS) reference frame, with the region spanning $\pm 30R_J$ in both dimensions highlighted in yellow. (b) A zoomed-in view of the highlighted region in (a), with individual *Galileo* PLS plasma flow speed measurements overplotted as points, colored according to MLT sector: dawn $(03 \le MLT < 09)$ in orange, noon $(09 \le MLT < 15)$ in yellow, dusk $(15 \le MLT < 21)$ in blue, and midnight $(00 \le MLT < 03; 21 \le MLT < 24)$ in purple. (c) A histogram of the number of *Galileo* PLS plasma flow speed measurements in each hour-wide MLT bin. The abundance of dawn and dusk observations, compared to those near noon and particularly near midnight, is evident.

 \hat{Z} aligned with Jupiter's rotational axis, the Sun located in the $\hat{X} - \hat{Z}$ plane, and \hat{Y} com-296 pleting the right-hand orthogonal set. The average plasma corotation rate (R_C) was cal-297 culated for bins spanning 1 hour in MLT and 2 R_J in ρ_e ; as the middle magnetosphere 298 is dominated by magnetic local time effects rather than longitudinal effects (Vogt et al., 299 2011; Ray et al., 2014), the *Galileo* data were not binned by the solar CML of the planet. 300 Binning of the plasma parameters was performed by averaging with weights proportional 301 to the inverse of the parameter variance to be representative of the time-averaged MI-302 coupled system. 303

The plasma corotation rate R_C is defined as

$$R_C = \frac{v_{flow}}{\rho_e \Omega_J} = \frac{\omega_{flow}}{\Omega_J} \tag{1}$$

where v_{flow} is the calculated linear plasma flow velocity from the Galileo PLS data, ω_{flow} 306 is the angular plasma flow velocity ($\omega_{flow} = v_{flow}/\rho_e$), and Ω_J is the angular veloc-307 ity at which Jupiter rotates $(1.76 \times 10^{-4} \text{ rad s}^{-1})$. R_C is averaged in each bin rather 308 than v_{flow} to account for the expected inverse relationship between equatorial distance 309 ρ_e and v_{flow} . When $v_{flow} = \rho_e \Omega_J$, the plasma is rigidly corotating with the planet and 310 $R_C = 1$. In turn, when $v_{flow} = 0$ then the plasma is fixed with respect to the Sun-311 Jupiter geometry, or effectively fixed in MLT, and $R_C = 0$. The full set of 6751 plasma 312 parameters used from *Galileo* PLS are summarized in Figure 4, which shows the two-313 dimensional distributions of the corotation rate R_C with respect to MLT and ρ_e . The 314 distributions of the standard deviations and number of measurements in each bin are pro-315 vided in Figure A2 for context in interpreting Figure 4. 316

317 **3 Analysis**

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The field-aligned current per radian of azimuth, $I_{||}$, flowing near the ionosphere in the coupled MI system responsible for accelerating electrons into Jupiter's ionosphere and driving the planet's ME can be found as

$$I_{||} = -2 \int_{0}^{\rho_{e}} j_{z} \rho'_{e} d\rho'_{e}$$
(2a)

$$=4\Sigma_P^*\Omega_J(1-R_c)F_e\tag{2b}$$



Figure 4. Two-dimensional distribution of the corotation rate R_C of the equatorial plasma from *Galileo* PLS moments from Equation 1 The moments were not binned with respect to solar CML, as the middle magnetosphere is expected to vary primarily in MLT. It is difficult to make out clear patterns in R_C , except that there is a slight tendency for higher values near dawn than near dusk.

adapted from Equation 16 in Cowley and Bunce (2001). Here j_z is the field-aligned cur-321 rent density flowing out of the current sheet lying in the middle magnetosphere's equa-322 torial region, Σ_P^* is the height-integrated effective Pedersen conductance, Ω_J and R_C are 323 as previously defined, and F_e is the equatorial magnetic flux function, a function which 324 maps the auroral ionosphere to the equatorial middle magnetosphere along contours of 325 constant magnetic flux. The field-aligned current per radian of azimuth $I_{||}$ can be cal-326 culated from the auroral brightness observed with HST using Equation 2a and from the 327 plasma flow speed derived from *Galileo* PLS using Equation 2b, as will be discussed in 328 Sections 3.1 and 3.2, respectively. 329

3.1 Field-aligned currents from HST observations

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The brightness of the ME aurorae observed with HST is directly proportional to the precipitated energy flux of auroral electrons E_f incident on the atmosphere, with a typical conversion factor of 10 kR per 1 mW m⁻². This conversion factor is an average of multiple studies (Gerard & Singh, 1982; Waite Jr. et al., 1983; Grodent et al., 2001; Gustin et al., 2012; Nichols & Cowley, 2022) which is expected to be valid for the range of precipitating electron energies (0.5 – 150 keV) (Gustin et al., 2012) expected to result from the field-aligned currents (Knight, 1973). This energy flux E_f is in turn related to the field-aligned current density just above the auroral ionosphere $j_{||}$ as

$$j_{||} = j_{||,0} \left(\pm \sqrt{2 \frac{E_f}{E_{f,0}} - 1} \right)$$
(3)

where $j_{||,0}$ is the maximum field-aligned current density above the ionosphere and $E_{f,0}$ 339 is the maximum precipitated energy flux of auroral electrons, both for the case of an ab-340 sence of field-aligned potentials. Equation 3 is derived by assuming the minimum nec-341 essary field-aligned potentials for currents to flow into the ionosphere. The maximum 342 energy flux in the absence of field-aligned potentials is $E_{f,0} = 2N \sqrt{W_{th}/2\pi m_e W_{th}}$ (Equa-343 tion 37 in Cowley and Bunce (2001)), which is a number flux of electrons $(2N\sqrt{W_{th}/2\pi m_e})$ 344 multiplied by a characteristic energy (W_{th}) . $E_{f,0}$ can therefore be estimated by measurable physical parameters; here, $N = 0.018 \text{ cm}^{-3}$ (Bagenal et al., 2016; Huscher et al., 345 346 2021) and $W_{th} = 5$ keV (Allegrini et al., 2021) are used. Similarly, the maximum field-347 aligned current density just above the ionosphere in the absence of field-aligned poten-348 tials is $j_{\parallel,0} = eN\sqrt{W_{th}/2\pi m_e}$, the number flux of electrons multiplied by e, the ele-349 mentary charge (Equation 28 in Cowley and Bunce (2001)). 350

The quantity j/B is constant along a magnetic field line provided there are no field-351 perpendicular currents intersecting the field line outside of the equatorial and ionospheric 352 regions (Cowley & Bunce, 2001), so $j_{||}$ can be written as $j_z B_i/B_e$, where B_i and B_e are 353 the strengths of the magnetic field along the field line in the ionosphere and the current 354 sheet in the equatorial plane, respectively. The magnetic field strength in the equato-355 rial plane of the magnetosphere B_e , is calculated from the form provided in Vogt et al. 356 (2011), which is itself a fit to in-situ magnetic field measurements from *Pioneer 10*, *Pi*-357 oneer 11, Voyager 1, Voyager 2, Ulysses, and Galileo spanning 20-120 R_J. The mag-358 netic field strength in the ionosphere was found using the internal magnetic field model 359 based on Juno's first 33 orbits of Connerney et al. (2022)(henceforth, JRM33), calcu-360 lated to order 13 using the code provided by Wilson et al. (2023), and assuming an al-361 titude of 1R_J. Vogt et al. (2011) The JRM33 internal field model is inappropriate for 362 use in the middle and outer magnetosphere, as the higher-order terms become negligi-363 ble and the resulting modeled field becomes unphysically azimuthally symmetric. The 364 form of the equatorial magnetic field B_e is adopted instead from Vogt et al. (2011) rather 365 than the Connerney et al. (2020) magnetodisk model to allow for the middle and outer 366 magnetosphere to vary with MLT. 367



Figure 5. Two-dimensional distributions of the integrated field-aligned current per radian of azimuth $I_{||}$ calculated from Equation 4 for the (a) northern and (b) southern hemispheres, with colors for each MLT- ρ_e bin corresponding to the colorbars to the right. Each distribution is labeled with the range of solar CMLs it covers; solar CML bins with no coverage are excluded. The hemispheric asymmetry seen clearly in Figure 2 is no longer evident after converting to field-aligned current. There is a general trend towards higher currents when the magnetosphere is more perturbed (i.e., when the ME maps to closer in regions of the magnetosphere) and a slight trend towards stronger currents near dusk than near dawn.

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Equation 3 can thus be substituted into Equation 2a for j_z to give

$$I_{||} = -2 \int_{0}^{\rho_{e}} j_{||,0} \frac{B_{e}}{B_{i}} \left(\pm \sqrt{2 \frac{E_{f}}{E_{f,0}}} - 1 \right) \rho_{e}' \, d\rho_{e}' \tag{4}$$

which can be used to calculate the field-aligned current per radian of azimuth $I_{||}$ cor-369 responding to a given auroral brightness. Evaluation of Equation 4 requires an integrable 370 auroral electron energy flux $E_f(\rho'_e)$, which in turn requires a function of the auroral bright-371 ness over equatorial distance. The variation of the auroral brightness with equatorial dis-372 tance illustrated in Figure 2 does not represent this function directly. Instead, these dis-373 tributions show the typical values of the observed ME when the ME maps to a given lo-374 cation in MLT- ρ_e space, which in turn represents the maximum of the field-aligned cur-375 rent density j_z for a given span of solar CML. An integrable radial distribution of $E_f(\rho'_e)$ 376 is therefore approximated as a Gaussian having a peak value of E_f , a center defined by 377 the corresponding radial bin, and a width defined by the angular width of the ME ($\delta\theta$) 378 magnetospherically mapped to a radial width ($\delta \rho_e$). The resulting radial distributions 379 are then numerically integrated from 0 out to the corresponding ρ_e value. The result-380 ing values of $I_{||}$ we report are thus average field-aligned currents per radian of azimuth 381 entering the ionosphere at the ME when the location of the ME maps to the current sheet 382 at the location specified by the corresponding bin. The distributions of $I_{||}$ with MLT, 383



Figure 6. Two-dimensional distribution of the quantity $I_{||}/\Sigma_P^*$ derived from the *Galileo* PLS moments using Equation 5, with colors in each MLT- ρ_e bin corresponding to the colorbar to the right. While the parameter $I_{||}/\Sigma_P^*$ is not strongly structured in either MLT or equatorial distance ρ_e , it can be seen to generally be smaller at dawn than at dusk, inverting the pattern seen in Figure 4.

 ρ_e , and solar CML in Figure 5 thus illustrate various independent MI coupling config-384 urations rather than multiple samples of the same configuration; similarly, the distribu-385 tions of the standard deviation of $I_{||}$ presented in Figure A3 represent the variability of 386 each of these configurations, rather than a level of confidence which varies with distance 387 ρ_e . To clarify further, the distributions of $I_{||}$ calculated here are not expected to increase 388 monotonically with equatorial distance ρ_e , even though the integral of $F_e(\rho'_e)$ would, for 389 the same reasons that the ME brightness does not increase monotonically with ρ_e in Fig-390 ure 2. 391

3.2 Field-aligned currents from Galileo-PLS data

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Returning to Equation 2b and rearranging, the total field-aligned current per radian of azimuth $I_{||}$ flowing into the ionosphere divided by the effective, height-integrated Pedersen conductance Σ_P^* of the ionosphere, can be found as

$$\frac{I_{||}}{\Sigma_P^*} = 4\Omega_J (1 - R_c) F_e \tag{5}$$

The height-integrated effective Pedersen conductance Σ_P^* is the sum of all conductance 396 terms and is reduced from the true value, Σ_P , by a factor of (1-k) to account for the 397 slippage in the ion-neutral coupling in the ionosphere. The values of k range from 0 < 0398 k < 1, with k = 0 corresponding to no slippage of the neutral atmosphere relative to 399 the planet's rigid rotation rate and $k \approx 1$ corresponding to maximal slippage (Huang 400 & Hill, 1989; Nichols & Cowley, 2003). The equatorial flux F_e , which relates locations 401 in the ionosphere to conjugate points in the current sheet in the equatorial plane of the 402 magnetosphere along contours of constant magnetic flux, is a function of both MLT and 403 ρ_e and is calculated using the form provided by Ray et al. (2014). This description of 404 $F_e(MLT, \rho_e)$ is based on a slightly modified version of the empirical magnetic field model 405 used to map HST observations into the equatorial magnetospheric plane (Vogt et al., 2011). 406 The differences between this and the unmodified empirical magnetic field model are great-407 est near the planet; the two descriptions agree throughout the middle magnetosphere where 408 MI coupling currents flow, ensuring consistency between the values derived from *Galileo* 409 PLS and HST observations. 410

The quantity $I_{\parallel}/\Sigma_{P}^{*}$ can thus be solved for using *Galileo* PLS-derived values of the 411 plasma corotation rate R_c and the known form of F_e . This quantity is introduced for 412 convenience and has limited physical meaning, despite having the form of an electric po-413 tential. Instead, the quantity $I_{||}/\Sigma_P^*$ groups unknown parameters together, and will al-414 low further exploration of the distribution of Σ_P^* when compared to the values of $I_{||}$ de-415 rived from HST observations. Figure 6 shows the distributions of the quantity $I_{||}/\Sigma_P^*$ 416 with MLT and equatorial distance ρ_e , while the standard deviations of each bin are in-417 cluded in Figure A4 for context. 418

419

4 Results and Discussion

420 4.1 Azimuthally integrated field-aligned currents

First, we focus on the field-aligned current per radian azimuth $I_{||}$ derived from HST 421 observations, which, unlike the parameter $I_{||}/\Sigma_P^*$ derived from *Galileo* measurements, 422 is representative of the field-aligned auroral currents flowing in Jupiter's coupled MI sys-423 tem without any further assumptions about the ionospheric Pedersen conductance. The northern ME is found to have a median current per radian of azimuth of $I_{||} = 9.34^{+5.72}_{-3.54}$ 425 MA rad⁻¹, while the southern ME has a median current per radian of azimuth of $I_{||} = 8.61^{+6.77}_{-3.05}$ MA rad⁻¹. These median values are found using a Monte Carlo bootstrap anal-426 427 ysis with lognormal error perturbation (henceforth just "medians"), in order to better 428 account for the measurement errors in the non-Gaussian distribution of currents (Curran, 429 2014). Upper and lower errors correspond to the 84^{th} and 16^{th} percentiles, respectively, 430 to approximate 1σ errors. 431

These median currents are in very good agreement with the currents calculated from 432 Juno magnetometer measurements. In the northern hemisphere, the median field-aligned 433 current compares favorably with the values of ~ 3.8 MA rad⁻¹ (within $\sim 1.6\sigma$) and ~ 5.4 434 MA rad⁻¹ (within $\sim 1.1\sigma$) and, considering that 95% of the currents calculated here have 435 values between $2.82 < I_{||} < 24.3$ MA rad⁻¹, aligns very well with the measured range 436 of ${\sim}1-27~{\rm MA~rad^{-1}}$ (Kotsiaros et al., 2019; Kamran et al., 2022; Nichols & Cowley, 437 2022, respectively). In the southern hemisphere, the median field aligned current agrees 438 more strongly with the value of ~9.2 MA rad⁻¹ (within ~0.09 σ) and lies well within the 439 same $\sim 1-27$ MA rad⁻¹ range as 95% of the calculated currents have values in the range 2.94 < $I_{||}$ < 25.8 MA rad⁻¹ (Kotsiaros et al., 2019; Nichols & Cowley, 2022, respec-440 441 tively). Each median current derived here is also in good agreement with hemisphere-442 symmetric MI coupling theory values of ~ 7.1 MA rad⁻¹ (within $\sim 0.5\sigma$ and $\sim 0.6\sigma$ for the northern and southern hemispheres respectively) (Cowley et al., 2008). The hemi-444 spheric asymmetry found from analysis of low-altitude Juno/MAG data (Kotsiaros et 445 al., 2019) is not recovered in the medians reported here, but some sense of this asymme-446 try is recovered by this analysis in that the reported 84^{th} percentile value of the south-447 ern median current is larger than that of the northern median current. Considering the 448 full two-dimensional distributions of the median currents $I_{||}$ found here, Figure 5 shows 449 that there is a slight tendency toward larger field-aligned currents near dusk rather than 450 near dawn, with occasional weak currents present near noon. This is qualitatively sim-451 ilar to the distribution of field-aligned current densities found from the magnetic field 452 signatures of lobe traversals within $30 R_{\rm J}$, and thus validates the importance of azimuthal 453 magnetodisk currents in determining the locations of field-aligned currents(Lorch et al., 454 2020).455

456

4.2 Effective Pedersen conductance

⁴⁵⁷ The effective Pedersen conductance (Σ_P^*) can be calculated by dividing the field-⁴⁵⁸ aligned current per radian of azimuth derived from HST measurements $I_{||}$ by the quan-⁴⁵⁹ tity derived from *Galileo* PLS moments $I_{||}/\Sigma_P^*$. Figure 7 shows distributions of this cal-⁴⁶⁰ culated effective Pedersen conductance for the northern and southern hemispheres; the



Figure 7. Two-dimensional distributions of the effective Pedersen conductance Σ_P^* for the (a) northern and (b) southern hemispheres, with the color of each MLT- ρ_e bin corresponding to the colorbars to the right. Each distribution is labeled with the range of solar CMLs it covers. The effective Pedersen conductance is only calculated where both HST-derived and *Galileo*/PLS-derived data are present; solar CML bins with no coverage are excluded. The conductance is generally greatest at smaller radial distances, as might be expected during a magnetospheric compression event where strong field-aligned currents are driven atypically close to the planet.

distributions of the standard deviation of the effective Pedersen conductance are shown in Figure A5 in order to provide a full picture of the variation. The binned distributions of $I_{||}/\Sigma_P^*$ are assumed to be the same at all solar CML in this analysis. We find 95% of conductances lie in the range $0.03 < \Sigma_P^* < 1.66$ mho in the north with a median of $\Sigma_P^* = 0.13^{+0.26}_{-0.07}$ mho and $0.03 < \Sigma_P^* < 2.40$ mho in the south with a median of $\Sigma_P^* = 0.16^{+0.34}_{-0.10}$ mho, with errors corresponding to the 16^{th} and 84^{th} percentiles.

For an average value of k = 0.55, well within typical values of $k \approx 0.4 - 0.7$ (Millward 467 et al., 2005), the values of the true Pedersen conductance we find are $\Sigma_P = 0.3^{+0.6}_{-0.2}$ mho 468 with 95% having values between 0.07~4 mho in the northern hemisphere and $\Sigma_P = 0.4^{+0.8}_{-0.2}$ 469 mho with 95% having values between $0.07 \sim 5$ mho in the southern hemisphere, where 470 we have rounded due to the large uncertainties in the value of k; for k = 0.7, the me-471 dian Pedersen conductances are as high as $\Sigma_P = 0.4^{0.9}_{-0.2}$ mho in the north and $\Sigma_P =$ 472 $0.5^{+1.1}_{-0.3}$ in the south. These averages are comparable to theoretical estimates (Millward 473 et al., 2002, 2005) but generally lower than recent estimates made using Juno ultravi-474 olet spectrograph (UVS) measurements and ionospheric modeling (Wang et al., 2021; 475 Al Saati et al., 2022) of $\Sigma_P \approx 2$ (within ~3.0 σ for k = 0.55 and ~1.8 σ for k = 0.7) 476 in the northern hemisphere and $\Sigma_P \approx 3$ (within $\sim 3.5\sigma$ for k = 0.55 and $\sim 2.2\sigma$ for k =477 (0.7) in the southern hemisphere. While some of this discrepancy may be attributed to 478 the uncertainty in k value, a more significant source likely lies in differences in methods 479

between studies. The mean values of Σ_P given by Al Saati et al. (2022) are calculated 480 using only peak values, while those reported here are averaged over the top quartile of 481 all values (Rutala et al., 2022). Visual inspection of maps of the Pedersen conductance 482 based on Juno/UVS data and ionospheric modeling suggests a somewhat lower typical 483 Pedersen conductance of $\Sigma_P \approx 1$ mho (within ~1.2 σ (k = 0.55) or ~0.7 σ (k = 0.7) 484 in the north and $\sim 0.9\sigma$ (k = 0.55) or $\sim 0.4\sigma$ (k = 0.7) in the south) when averaged 485 over a wider range immediately surrounding the ME. A general north-south symmetry 486 in the mean Pedersen conductance is common to our results, theoretical models (Millward 487 et al., 2002, 2005), and Juno/UVS-based findings (Gérard et al., 2020, 2021; Wang et 488 al., 2021; Al Saati et al., 2022). 489

For clarity, Figure 8 shows the same data as Figure 7, but with the medians and 490 the $84^{th}/16^{th}$ percentile errors of the effective Pedersen conductance in each bin plot-491 ted. By comparison to the average values and errors for each hemisphere overall, the vari-492 ations in conductance with respect to each binning parameter can be seen. Figures 8c 493 and 8f show that Σ_P^* varies minimally with solar CML. Figures 8b and 8e show that the 494 effective Pedersen conductance is generally higher at smaller radial values, correspond-495 ing to higher field-aligned currents when the magnetosphere is in a disturbed enough state 496 for the ME to map to these distances. The conductance thus increases with current, as 497 expected (Nichols & Cowley, 2004). The bin-to-bin variation is greatest when the con-498 ductance is interpreted as a function of MLT, as shown in Figures 8a and 8d. This sig-499 nificant variation in effective conductance with MLT is more likely than the variations 500 with equatorial distance or solar CML to be related to the local time asymmetries in the 501 appearance, distribution, and motion of ME aurorae. Both hemispheres display peaks 502 in the effective conductance between 6-9, 12-13, and 14-15 MLT. It is worth not-503 ing that, without the limb-brightening correction applied to HST-observed auroral bright-504 ness, derived field-aligned currents would be increased more near dawn and dusk than 505 near noon, and Σ_P^* would increase proportionally. The overestimation of the limb-brightening 506 correction factors thus results in an underestimation of the conductance near the planet's 507 limbs at dawn and dusk, and a more accurate model of Jupiter's limb-brightening would 508 heighten the peak in Σ_P^* between 6 – 9 MLT further than the others. 509



Figure 8. Plots more clearly showing the trends in the median effective Pedersen conductance Σ_P^* with MLT (a, d), ρ_e (b, e), and solar CML (c, f) for the northern (a, b, c; blue circles) and southern (d, e, f; red triangles) hemisphere ME. The overall median effective Pedersen conductance (dashed line) along with the 84th and 16th percentile errors (gray shaded region) on this value are shown for context. The conductance is generally higher near dawn than elsewhere within the ME, and higher at smaller radial distances as seen in Figure 7. In contrast, the conductance varies insignificantly with solar CML.

Figure 9 shows the complete conductance distributions mapped onto Jupiter's au-510 roral ionosphere for each solar CML bin, allowing the variation in Σ_P^* with local time 511 and location relative to the SMO to be visualized. The generally increased effective Ped-512 ersen conductance near local dawn, located to the left of each frame in Figure 9, is ev-513 ident. The smooth decrease in Σ_P^* with increasing ρ_e can be seen as a decrease in Σ_P^* 514 with increasing latitude, particularly in the noon and dusk sectors, in Figure 9a. The 515 same trend is not seen in Figure 9b, as the middle magnetosphere maps to a smaller range 516 of latitudes in the southern ME than in the northern ME. 517



Figure 9. Polar, orthographic views of Jupiter's northern (a) and southern (b) auroral regions, with the derived Σ_P^* distributions shown mapped onto the planet by mapping MLT and ρ_e onto λ_{III} and ϕ . Each frame corresponds to one solar CML bin as labeled above with the mean solar CML, and hence noon local time, located at the bottom of the frame the northern hemisphere (a) and at the top of the frame in the southern hemisphere (b); solar CML bins with no coverage are excluded. The SMO (red dashed line) (Nichols et al., 2009) and λ_{III} and ϕ graticules (yellow lines) are shown. Values of Σ_P^* have been log-scaled and correspond to the colorbar to the right. The increased conductance near dawn (left of each frame) can be seen, as can the increased conductance at lower latitudes (mapping to smaller ρ_e).

From the derived distributions of Σ_{P}^{*} alone, we cannot determine the cause of the variation of the conductance with MLT. It is of interest, however, that the effective Pedersen conductance peaks in the late-dawn (6 - 9 MLT) and noon (12 - 13 MLT) regions are generally colocated with known subcorotating emission features within the ME: the dawn storms and associated, less bright subcorotating emission features in the postdawn region (Rutala et al., 2022) and the noon discontinuity and auroral spot near noon (Radioti et al., 2008; Palmaerts et al., 2014).

The co-occurrence of increased ionospheric conductance and subcorotating auro-525 ral features within the ME was hypothesized by Rutala et al. (2022) as an explanation 526 of subcorotational behavior near dawn. The basic premise being that, if the ionospheric 527 conductance is locally increased for a reason unrelated to MI-coupling currents, the MI-528 coupling currents will increase in magnitude due to the heightened conductance, accel-529 erating magnetospheric plasma up to the corotation rate of the planet; as the magne-530 tosphere generally compresses from dawn through noon, the linear velocity of the recently-531 accelerated magnetospheric plasma would exceed the local angular corotational veloc-532 ity as the system rotates, thus reducing or reversing the field-aligned currents. In the iono-533 sphere, this would appear as a bright auroral form associated with the increased currents 534 which ends abruptly as the currents reverse, thus appearing fixed in local time. This pic-535 ture meshes well with the noon ME discontinuity observed by Radioti et al. (2008), which 536 is expected to be associated with reduced or reversed field-aligned currents. The secondary 537 peak in Σ_P^* near noon may be associated with the subcorotational noon auroral spot (Palmaerts 538 et al., 2014), as following noon the magnetosphere expands again, thus requiring increased 539 field-aligned currents to bring plasma up to local corotational velocity. 540

This second peak in Σ_P^* near 12 MLT may instead be caused by increased field-541 aligned currents caused by shearing motions of magnetospheric plasma, as modeled by 542 Chané et al. (2018). Generally, as an increase in the field-aligned currents will cause an 543 increase in the effective Pedersen conductance, we cannot distinguish between cause and 544 effect with this data set: high currents could cause increased conductance, or heightened 545 conductance may drive increased currents. It is of note that the conductance distribu-546 tions found in Figure 8 are more similar to the modeled conductance distribution in LT 547 found by Tao et al. (2010) than to the distributions in solar CML found by Gérard et 548 al. (2020, 2021) from ionospheric modeling based on Juno/UVS data. In the latter case, 549 the differences may in part be explained by the difference in observational integration 550 time. Images from HST span non-overlapping 30-100 s exposures while spectral im-551 ages from Juno/UVS were integrated over 20-50 min (Gérard et al., 2020, 2021), which 552 would introduce more smoothing into the Juno UVS based maps than is present in this 553 analysis. Further, the differences in methodology between the spatial analysis of Gérard 554 et al. (2020), which is a case study of 8 individual Juno orbits, and the long-term sta-555 tistical study presented here may contribute significantly to the apparent differences be-556 tween the two. A careful comparison between Juno/UVS-derived conductance and con-557 temporary Juno/JADE-derived plasma flow, similar to the analysis performed here, is 558 needed to fully explore these potential differences. Conversely, the similarity in form be-559 tween the Σ_{P}^{*} distributions found here and those of Tao et al. (2010) may indicate a re-560 lationship between heightened dawn sector conductance and incident solar extreme ul-561 traviolet (EUV) photons, which increase the Pedersen conductance by ionizing the iono-562 sphere. 563

564 5 Conclusions

We have outlined a novel method for deriving values of the effective Pedersen con-565 ductance Σ_P^* of Jupiter's ME auroral ionosphere by combining remote observations of 566 the Jovian ME and in-situ observations of the angular velocity, or corotation rate, of mid-567 dle magnetospheric plasma. This method has been developed from the theoretical un-568 derstanding of MI coupling at Jupiter, which links the field-aligned currents entering the 569 ionosphere, estimated from the auroral brightness measured with HST, to the motion 570 of middle magnetospheric plasma, calculated by moment analysis of Galileo PLS mea-571 surements. Equivalent regions of the auroral ionosphere and equatorial magnetosphere 572 are found using magnetic flux equivalence mapping. The non-overlapping 288 HST ob-573 servations and 6751 *Galileo* measurements used in this analysis are taken to be repre-574 sentative of the time-averaged Jupiter system. 575

Combining HST-derived estimates of the field-aligned currents per radian of az-576 imuth $I_{||}$ with the parameter $I_{||}/\Sigma_P^*$ derived from in-situ Galileo PLS measurements, we 577 find the effective Pedersen conductance Σ_P^* , reduced from the true Pedersen conductance 578 by a factor of 1-k. Σ_P^* ranges between $0.03 < \Sigma_P^* < 1.66$ mho in the north and $0.03 < \Sigma_P^* < 2.40$ mho in the south, with typical values of $\Sigma_P^* = 0.13^{+0.26}_{-0.07}$ mho and $\Sigma_P^* = 0.16^{+0.34}_{-0.10}$ 579 580 mho in the northern and southern ME, respectively. These typical values are broadly 581 consistent with theoretical and modeled values (Millward et al., 2002, 2005; Gérard et 582 al., 2020, 2021) and slightly lower than estimates based on Juno/UVS measurements (Wang 583 et al., 2021; Al Saati et al., 2022); these differences may partially be explained by sig-584 nificant uncertainty in appropriate values of k, as well as by differing methods of char-585 acterizing the UV emission between these studies and that presented here. Unlike these previous studies, the distributions of Σ_P^* we find reveal that it varies significantly in MLT. 587 In calculating $I_{||}$ from HST observations in order to determine Σ_P^* , we additionally find 588 independent estimates of the field-aligned currents entering the ionosphere of $I_{||} = 9.34^{+5.72}_{-3.54}$ MA rad⁻¹ and $I_{||} = 8.61^{+6.77}_{-3.05}$ MA rad⁻¹, corresponding to the northern and southern 589 590 ME, respectively, in quantitative agreement with recent Juno-based measurements (Kotsiaros 591 et al., 2019; Nichols & Cowley, 2022; Kamran et al., 2022) and theoretical estimates (Hill, 592 2001; Cowley & Bunce, 2001; Cowley et al., 2008). The distributions of field-aligned cur-593 rents $I_{||}$ found here also qualitatively agree with the distribution found from multi-spacecraft 594 magnetometer analysis, which shows stronger field-aligned current densities near dusk 595 than near dawn (Lorch et al., 2020). Taking these results together, this analysis indicates 596 that the field-aligned currents derived from MI coupling theory, which have historically 597 been used to explain Jupiter's ME, are an adequate description of the relationship be-598 tween ME auroral brightness and the motion of middle magnetospheric plasma. 599

The measurement of heightened effective Pedersen conductances near MLTs of 6– 600 9 and 12-13 MLT is an interesting result, as these elevated conductances are approx-601 imately co-located with auroral features in the ME with subcorotational motions (Rutala 602 et al., 2022; Radioti et al., 2008; Palmaerts et al., 2014). The results we present thus sup-603 port the theory that ionospheric Pedersen conductance is key to controlling the motions 604 of subcorotational auroral features and are compatible with the theory that the motions 605 of subcorotational auroral features in the dawn sector are modulated by solar EUV ion-606 ization in the auroral ionosphere (Rutala et al., 2022). We cannot, however, distinguish 607 between this case and the case of otherwise-increased dawn currents causing locally el-608 evated conductances. Breaking the observational degeneracy between these cases should 609 be done with comparisons of the distributions found here to models of the field-aligned 610 currents flowing in the MI coupling system under varying ionospheric conductance con-611 ditions. 612

⁶¹³ Appendix A Additional Two-Dimensional Distributions

The two-dimensional distributions of parameters previously discussed represent sta-614 tistical averages of the large dataset used here. As such statistical averages are of lim-615 ited use and difficult to interpret when presented alone, here the two-dimensional dis-616 tributions of the standard deviations of the parameters and of the number of measure-617 ments used are presented. The standard deviations and numbers are provided for the 618 auroral brightness in Figure A1 and for the corotation rate R_C in Figure A2. Only the 619 standard deviations, not the total numbers of measurements used, are presented for the 620 derived quantities, including: the field-aligned current per radian of azimuth $I_{||}$ in Fig-621 ure A3, the field-aligned current per radian of azimuth per unit conductance I_{\parallel}/Σ_P^* in 622 Figure A4, and the effective Pedersen conductance Σ_P^* in Figure A5. In all these distri-623 butions, the standard deviations are presented as the fractional standard deviation, or 624 the ratio of the standard deviation to the value in the bin σ/μ . The resulting distribu-625 tions are therefore unitless, and the relative scale of the standard deviation can be in-626 terpreted without direct comparison to the two-dimensional distribution of the relevant 627 parameter. 628

629 Open Research

All Hubble Space Telescope observations used in this analysis are available at the 630 Mikulski Archive for Space Telescopes hosted by the Space Telescope Science Institute, 631 and have been collected into a single dataset for ease of access (Rutala, 2022). All Galileo 632 PLS real-time-science data are available through the Planetary Plasma Interaction (PPI) 633 node of the Planetary Data System (PDS) (Frank et al., 2023). This research made use 634 of the ionosphere-magnetosphere mapping code of Vogt et al. (2011) and the internal mag-635 netic field model of Connerney et al. (2022) as made available by Wilson et al. (2023) 636 to allow comparison between in-situ and remote measurements, as well as the MLT-varying 637 magnetodisk models of Vogt et al. (2011) and Ray et al. (2014). For reproducibility, in-638 termediate data products in the form of the HST-derived ME samples and Galileo/PLS-639 derived plasma samples are catalogued at https://doi.org/10.5281/zenodo.10563000 640 (Rutala et al., 2024). 641

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Figure A1. Two-dimensional distributions of the (a, c) fractional standard deviation and (b, d) number of measurements of the auroral brightness in the (a, b) northern and (c, d) southern hemispheres, as in Figure 2. Each distribution is labeled with the corresponding range of solar CMLs it spans; solar CML ranges for which there are no observations were excluded. The color of each MLT- ρ_e bin corresponds to the colorbar to the right of each set of distributions. It is evident that there are more observations of the northern hemisphere than the southern hemisphere ME. Typical standard deviation values are around 0.2 - 0.4 (20 - 40% of the brightness value in that bin), with some notably high bins near 1.0; as these high-valued bins frequently have high numbers of observations, these standard deviations are not likely to be caused by a small number of outliers but instead are representative of real changes in ME auroral brightness.



Figure A2. The same as Figure A1, but for (a) the fractional standard deviation and (b) the number of measurements of the magnetospheric plasma corotation rate R_C , as in Figure 4. Values of the fractional speed near 1 in bins with relatively high numbers of measurements indicates that there is a large range of measured speeds in Jupiter's middle magnetospheric plasma.

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Figure A3. The same as Figure A1, but for the fractional standard deviation of the fieldaligned currents per radian of azimuth $I_{||}$ in the (a) northern and (b) southern hemispheres, as in Figure 5. The distributions are similar to those of the fractional standard deviation in Figure A1, with high fractional standard deviations representing the true variation of the system rather than uncertainty.



Figure A4. The same as Figure A2, but for the fractional standard deviation of the derived quantity $I_{||}/\Sigma_P^*$, as in Figure 6. Compared to the fractional standard deviation shown in Figure A2, here the bins with large relative standard deviations have been made significantly more obvious owing to the conversion from R_C , which varies between 0 - 1 to $I_{||}/\Sigma_P^*$, which varies over more than two orders of magnitude.



Figure A5. The same as in Figure A1, but for the fractional standard deviations of the effective Pedersen conductance in the (a) northern and (b) southern hemispheres, as in Figure 7. As expected, the fractional standard deviations take on aspects of both those of the field-aligned currents $I_{||}$ (Figure A3 and that of the quantity $I_{||}/\Sigma_P^*$ (Figure A4); as the quantity $I_{||}/\Sigma_P^*$ does not vary with solar CML, its effects are especially evident in the form of bins with fractional standard deviations near 1. As before, these large fractional standard deviations co-occur with large numbers of observations, and thus are expected to be representative of the physical variation in the system rather than a measure of uncertainty.

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Variation in the Pedersen Conductance near Jupiter's Main Emission Aurora: Comparison of Hubble Space Telescope and Galileo Measurements

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Key Points:

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10	•	The effective ionospheric Pedersen conductance in Jupiter's main emission auro-
11		ral region is derived from remote and in-situ measurements.
12	•	Field-aligned auroral currents of $\sim 10 \text{ MA rad}^{-1}$ and effective Pedersen conduc-
13		tances of ~ 0.14 mho are derived, consistent with past research.
14	•	The effective Pedersen conductance varies primarily in magnetic local time, and
15		may explain the enigmatic motions of some auroral forms.

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16 Abstract

We present the first large-scale statistical survey of the Jovian main emission (ME) to 17 map auroral properties from their ionospheric locations out into the equatorial plane of 18 the magnetosphere, where they are compared directly to in-situ spacecraft measurements. 19 We use magnetosphere-ionosphere (MI) coupling theory to calculate currents from the 20 auroral brightness as measured with the Hubble Space Telescope and from plasma flow 21 speeds measured in-situ with the *Galileo* spacecraft. The effective Pedersen conductance 22 of the ionosphere (Σ_P^*) remains a free parameter in this comparison. We first show that 23 the field-aligned currents per radian of azimuth calculated from the auroral observations, 24 found to be $I_{||} = 9.54^{+11.5}_{-6.35}$ MA rad⁻¹ and $I_{||} = 10.64^{+11.1}_{-6.11}$ MA rad⁻¹ in the north and south, respectively, are consistent with previous results. Then, we calculate the Peder-25 26 sen conductance from the combined datasets, and find it ranges from $0.02 < \Sigma_P^* < 2.26$ 27 mho overall with averages of $0.14^{+0.31}_{-0.08}$ mho in the north and $0.14^{+0.26}_{-0.09}$ mho in the south. 28 Taking the currents and effective Pedersen conductance together, we find that the av-29 erage ME intensity and plasma flow speed in the middle magnetosphere (10-30 R_J) are 30 broadly consistent with one another under MI coupling theory. We find evidence for peaks 31 in the distribution of Σ_{P}^{*} near 7, 12, and 14 hours magnetic local time (MLT). This vari-32 ation in Pedersen conductance with MLT may indicate the importance of conductance 33 in modulating MLT- and local-time-asymmetries in the ME, including the apparent sub-34 corotation of some auroral features within the ME. 35

³⁶ Plain Language Summary

The brightest part of Jupiter's aurorae- the main emission- forms arcs of sheet-37 like lights surrounding both magnetic poles, similar to the Earth's aurorae. At both plan-38 ets, these lights are caused by charged particles flowing into the planet's atmosphere, where 39 they collide with gases and glow. At Jupiter, these particles are electrons which flow in 40 electrical currents connecting the planet to the charged-particle-filled space surround-41 ing it. Here, we use Hubble Space Telescope images of Jupiter's aurorae spanning a decade 42 to build up an average picture of the brightness and location of this main emission. The 43 brightness is related to the energy of the electrons, which in turn is related to the strength 44 of electrical currents flowing near the planet. We then use particle measurements made 45 by the Galileo spacecraft in orbit around Jupiter to make an average picture of these par-46 ticle's as they move around Jupiter. These speeds are related to the same electrical cur-47 rents, but include an electrical conductivity term describing how easily currents flow through 48 Jupiter's auroral atmosphere. We combine all these measurements to calculate the con-49 ductivity, and present results which are consistent with expectations but which fluctu-50 ate more quickly than expected in parts of the main emission. 51

52 1 Introduction

Jupiter's ultraviolet (UV) auroral main emission (ME), typically the most power-53 ful component of the planet's large-scale auroral regions, takes the form of a partially-54 closed oval of auroral emission surrounding each of the planet's magnetic poles. The Jo-55 vian aurorae are detectable at all local times (LT) including on the planet's dayside(Clarke 56 et al., 2004; Bonfond et al., 2017), where they are significantly brighter than Jupiter's 57 surface UV emission (Gustin et al., 2012) and can thus be observed routinely with the 58 Hubble Space Telescope (HST). In the southern hemisphere, the ME forms a nearly cir-59 cular curtain of light; however, the presence of multiple significant non-dipolar magnetic 60 field components in the northern hemisphere complicates the structure, resulting in a 61 characteristic 'kidney bean' shape (Grodent et al., 2008; Connerney et al., 2022), as shown 62 by the HST observation and statistically-averaged reference main oval ('statistical main 63 oval', or SMO) in Figure 1a. 64

The ME has historically been thought to originate from the magnetosphere-ionosphere 65 (MI) coupling currents flowing in the Jovian middle magnetosphere, radially outward in 66 the equatorial plasma disc, equatorward in the ionosphere, and along magnetic field lines 67 between (Hill, 2001; Cowley & Bunce, 2001; Nichols & Cowley, 2003, 2004, 2005; Ray 68 et al., 2010, 2014; Smith & Aylward, 2009; Tao et al., 2009). This current system arises 69 from the azimuthal distortion (or 'bendback') of the field caused by the planet's reser-70 voir of angular momentum opposing the decrease in angular velocity of flux tubes laden 71 with Iogenic plasma as they diffuse radially outward . In the absence of torques, these 72 diffusing flux tubes would tend to conserve angular momentum, resulting in a decrease 73 in the angular velocity proportional to r^{-2} . The resultant lag in the flux tubes corre-74 sponds to an azimuthal bendback in the magnetic field structure and thus a loop of field-75 aligned current which acts to partially enforce the corotation of the plasma composing 76 the plasma disk by exerting a $\mathbf{J} \times \mathbf{B}$ force in the direction of corotation. The strongest 77 field-aligned currents occur near where rigid corotation breaks down (Hill, 1979; Nichols 78 & Cowley, 2004). The ME current system is characterized primarily by the rapid ro-79 tation and strength of Jupiter's magnetic field, rather than by solar influence as is the 80 case in the Earth's own magnetosphere and auroral ovals (Cowley & Bunce, 2001; South-81 wood & Kivelson, 2001), though solar wind influence is not completely absent (Kita et 82 al., 2019; Nichols et al., 2017). These MI-coupling currents and the associated ME ovals 83 are thus always present, owing to the continuous production of Iogenic plasma and dif-84 fusion of this plasma outward through the magnetosphere. 85

The production and diffusion of Iogenic plasma is not constant and the Jovian mag-86 netosphere is varies in System III (SIII) magnetic longitude (λ_{III}), local time (LT), and 87 magnetic local time (MLT). This results in various asymmetries in the brightness, shape, 88 distribution, and dynamics of auroral forms within the ME oval. The southern ME is 89 brighter on average than the northern (Gérard et al., 2013) and the dusk side of the ME 90 is brighter on average than dawn, an effect which is amplified in the brighter southern 91 hemisphere (Bonfond et al., 2015). On occasions where the dawn side is brighter than 92 dusk, an exceptionally bright auroral feature – a dawn storm, perhaps – is typically lo-93 cated on the dawn ME (Gérard, Grodent, et al., 1994; Bonfond et al., 2021; Rutala et 94 al., 2022). While the locations of the ME remain fixed in SIII longitude and latitude (Clarke 95 et al., 2004; Gérard, Dols, et al., 1994; Grodent et al., 2003), auroral features on the ME 96 may subcorotate, lagging behind the rigid corotation rate of the planet. Subcorotation 97 occurs more often in the dawn sector than the noon and dusk sectors (Rutala et al., 2022). 98 an effect which appears to be separate from the appearance of bright dawn storms. Ad-99 ditional subcorotating auroral forms, the ME auroral discontinuity (Radioti et al., 2008) 100 and small-scale brightening (Palmaerts et al., 2014) are observed localized near noon. 101 The dusk side of the ME as viewed from the Earth is typically wider and more diffuse 102 than near dawn (Gérard, Dols, et al., 1994); this asymmetry is larger in the northern hemi-103 sphere, where the northern magnetic anomaly is typically located in remote observations 104 (Grodent et al., 2008). This asymmetry was originally considered to be a variation in 105 local time (Caldwell et al., 1992), before improved HST observations made it appear to 106 be a variation in SIII longitude (Gérard, Dols, et al., 1994). Recent Juno observations 107 of the ME oval morphology indicate that this asymmetry may vary in a more complex 108 way, dependent on both local time and SIII longitude (Greathouse et al., 2021). 109

These phenomena have generally been thought to arise from deviations from the 110 ideal axisymmetric MI-coupling theory previously discussed. However, predictions of 111 this theory are not always in accordance with observations, raising the possibility that 112 the MI-coupling theory itself only partially describes the generation of the ME oval at 113 Jupiter (Bonfond et al., 2020). Mean field-aligned MI-coupling currents of 58 MA and 114 24 MA in the southern and northern ME regions, respectively, have been derived from 115 Juno measurements, reflecting the observed north-south brightness asymmetry of the 116 ME ovals (Kotsiaros et al., 2019). These currents appear in primarily longitudinal, though 117 variable, sheets in keeping with the schematic picture of MI coupling theory. Further Juno 118

measurements have found that the field lines associated with ME aurorae host precip-119 itating electrons, as required to drive field-aligned currents, along with bi-directional elec-120 tron distributions (Mauk et al., 2017, 2018), suggesting that additional auroral emission 121 zones, co-located or nearly co-located with the ME, may be driven by acceleration pro-122 cesses other than field-aligned potentials (Mauk et al., 2020). The measured bi-directional 123 electron distributions may, however, be a secondary effect, driven by the flow of intense 124 field-aligned currents (Nichols & Cowley, 2022). The equatorial radial currents derived 125 from Juno magnetometer measurements are highly correlated with simultaneous HST 126 observations of the dawnside ME auroral intensity (Nichols & Cowley, 2022). On large 127 scales, the MI-coupling theory still explains the bulk of the observed variation in ME au-128 roral brightness, including during short-term enhancements (Nichols et al., 2020). 129

A further discrepancy between the modeled and observed auroral MI-coupling sys-130 tem at Jupiter lies in the auroral brightness asymmetry across the dayside ME. While 131 the dusk side of the ME oval is typically observed to be brighter than the dawn side (Bonfond 132 et al., 2015), models predict that this asymmetry should be reversed owing to the larger 133 field bend-back in the dawn sector (Ray et al., 2014). Field bend-back is strongly cor-134 related with ME auroral brightness, particularly near dawn (Nichols & Cowley, 2022). 135 Field bend-back is caused by angular plasma flow speeds in the middle magnetosphere 136 slower than the rotation rate of the planet, or subcorotation relative to the planet's ro-137 tation, so in considering only the quasi-steady-state MI coupling current system, an an-138 ticorrelation between the degree of field bend-back and plasma angular velocity is ex-139 pected (Bonfond et al., 2020). A partial ring current, spanning the nightside middle mag-140 netosphere with a source near dusk and a sink near dawn (Walker & Ogino, 2003) may 141 ease this tension if the ring current closes along field-aligned currents, decreasing the ef-142 fective field-aligned currents near dawn and increasing them near dusk (Bonfond et al., 143 2015). On top of this effect, careful consideration is required to relate instantaneous, in-144 situ measurements of plasma velocity to the measurement of magnetic field bend-back 145 in a dynamic region of the magnetosphere such as the dawn sector. The anticorrelation 146 between field bend-back and plasma velocity is only maintained in the quasi-steady-state 147 scenario. If magnetospheric plasma near dawn is rapidly accelerated, the measured plasma 148 velocity may be high despite large degrees of field bend-back, as the plasma and field lines 149 have yet to "catch up" to corotational velocity. This scenario matches observations of 150 both the plasma (Krupp et al., 2001; Bagenal et al., 2016) and the magnetic field (Khurana 151 & Schwarzl, 2005) near dawn. Such a sudden acceleration of the middle magnetospheric 152 plasma may be driven by an equally sudden increase in the conductance of the MI-coupling 153 circuit, as is the case near the dawn terminator where the previously-unlit ionosphere 154 is re-photoionized by solar extreme ultraviolet (EUV) light (Tao et al., 2010). This sce-155 nario has been suggested to explain the apparent subcorotation of some auroral forms 156 relative relative to the SMO in the dawn sector (Rutala et al., 2022), and will be explored 157 here in more detail. 158

Here, we present the first large-scale statistical survey of the typical HST-observed 159 ME brightness, spanning more than 10 years and 200 cumulative hours of exposure time. 160 The ME brightness is mapped from the polar ionosphere out into the magnetospheric 161 equatorial plane and averaged in bins defined by MLT, equatorial radial distance (ρ_e), 162 and the solar central meridian longitude (solar CML), so that variations relative to MLT 163 and λ_{III} can be differentiated. From these binned values, the associated maximum field-164 aligned current density and total currents under MI-coupling theory are derived. We com-165 pare the derived total currents from this novel analysis of HST observations to litera-166 ture values, finding good agreement in scale. These values are then compared to non-167 contemporaneous in-situ Galileo Plasma Science (PLS) measurements of the plasma flow 168 speed and associated field-aligned current density and total current binned in the same 169 way as the HST observations in order to perform a superposed epoch analysis. Finally, 170 we compare the HST- and *Galileo*- derived currents directly, assuming that they fully 171 describe the large-scale, time-averaged state of the MI-coupling system, to derive a dis-172



Figure 1. Plots showing multiple views of Jupiter's northern ME on May 22, 2016 beginning at 18:02:46 UTC, as observed with HST STIS. Panel (a) shows a top-down, polar view of the northern ME, with the statistical main oval (SMO) shown with a red dashed line and λ_{III} and latitude graticules in yellow. Panel (b) shows a labeled keogram, where the observation in (a) is represented in the first (top) row. The values in both (a) and (b) are log-scaled with colors corresponding to the colorbar beneath. Panel (c) depicts the same keogram, but with a limb-brightening correction applied. Panel (d) shows the corrected keogram projected to the magnetospheric equatorial plane as a function of MLT and ρ_e , with the projected SMO corresponding to the first (dashed) and final (dotted) exposures shown in red. The values in both (c) and (d) are log-scaled, with colors corresponding to the separate colorbar beneath.

tribution of the Pedersen conductance in MLT, ρ_e , and solar CML. The resulting conductance distribution is additionally mapped back into the ionosphere. We find that the Pedersen conductance peaks in the dawn sector, and varies primarily in MLT, consistent with controlling the subcorotation of auroral forms in the dawn ME and helping resolve the tension between high degrees of field bend-back and high plasma velocities in the dawn sector.

179 2 Data

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2.1 Hubble Space Telescope Data

Archival observations of Jupiter's ultraviolet (UV) aurorae made with the Advanced Camera for Surveys Solar Blind Channel (ACS/SBC) and Space Telescope Imaging Spectrograph (STIS) on HST were obtained for this study. These observations comprise more than 200 cumulative hours of exposure, and span 2007 and 2016–2019; this large survey is expected to be representative of the general state of Jupiter's main emission aurorae. Further details about this set of observations are presented in Rutala et al. (2022) and references therein.

Time-tagged STIS observations were split into non-overlapping 30s intervals to cre-188 ate images, while the typical ~ 100 s exposures for the ACS observations were unchanged. 189 Images were reduced and projected onto an equirectangular planetocentric grid using the 190 standard procedures in the Boston University HST data reduction pipeline (Clarke et 191 al., 2009; Nichols & Cowley, 2022; Rutala et al., 2022, e.g.); the projection from the HST 192 perspective to an equirectangular grid allows the observations to be viewed from any per-193 spective, as illustrated by the reduced observation mapped to an orthographic polar view 194 in Figure 1a. The factors used to convert the observed auroral brightness from counts/s 195 to kR of unabsorbed H and H_2 emission vary with color ratio (Gustin et al., 2012), which 196 can change rapidly on both small and large scales. Here, we estimate an effective value 197 of the color ratio of 12 in the ME region from Juno ultraviolet spectrograph (UVS) based 198
maps of the color ratio distribution (Gérard et al., 2018). Auroral intensities in the ACS/SBC
images were further multiplied by a factor of 1.4 for those using the F115LP filter and
1.6 for those using the F125LP filter, following recent changes to the SBC absolute flux
calibration (Avila et al., 2019).

In each reduced image, an ME brightness profile is measured as the mean bright-203 ness of the brightest quartile of emission within $\pm 5^{\circ}$ perpendicular to the SMO, as found 204 by Nichols et al. (2009), in steps along the ME. 300 steps evenly spaced in distance along 205 the SMO with dynamic sizes were found to maximize resolution while preventing over-206 lap between pixels sampled by adjacent steps. The extracted brightness profile is stacked 207 into a keogram for each image within the same HST visit, and aligned such that the lo-208 cation along the SMO is measured horizontally and exposure time is measured vertically. 209 Figure 1b shows a keogram created in part from the observation in Figure 1a, with SIII 210 coordinates, distance along the SMO, and MLT all labeled. Limb-brightening correction 211 factors found as the inverse cosine of the view angle (Grodent et al., 2005) were applied 212 to each keogram, the results of which are demonstrated in Figure 1c. The inverse-cosine 213 correction generally overestimates the limb-brightening effect very near the edge of planet's 214 disk as viewed by HST. The effect of this overestimation is partially countered by remov-215 ing all parts of the observations within 10° of the limb; the slight remaining effects of 216 the overestimation will be discussed in the Results. The keogram production process is 217 further discussed in Rutala et al. (2022). 218

In each of the 288 keograms, the auroral brightness (I), local time (LT), latitude 219 (ϕ) , System III longitude (λ_{III}) , and the 1σ width $(\delta\theta)$ of the ME were recorded for ev-220 ery pixel. Pixels were then mapped from λ_{III} and ϕ in the ionosphere to magnetic lo-221 cal time (MLT) and radial distance in the equatorial plane of the mangetosphere (ρ_e) 222 using the magnetic flux equivalence mapping of Vogt et al. (2011). The internal mag-223 netic field for the mapping was specified to be the JRM09 magnetic field model (Connerney 224 et al., 2018) which, over the spatial scales relevant here, is very similar to the more re-225 cent JRM33 model (Connerney et al., 2022). Solar CML values for the mapping were 226 found using ephemerides from the NASA NAIF SPICE toolkit (Acton et al., 2018). The angular width of the ME, $\delta\theta$, was mapped to a radial width, $\delta\rho_e$, in the same manner. 228 The observed and mapped parameters were then binned by 1 hour in MLT, 2 R_J in ρ_e , 229 and 24° in solar CML; a typical, 40 minute HST observation of the Jovian aurorae spans 230 $\sim 24^{\circ}$ of longitude as the planet rotates. Values in each bin were calculated as the arith-231 metic mean. Figure 1d shows the auroral brightness of the keogram in Figure 1c binned 232 in MLT and ρ_J , with the projected SMO locations corresponding to the first and last 233 exposures included for reference. As Figure 1d represents a ~ 40 min. observation, it 234 effectively spans a single bin in solar CML and can as such be binned in MLT and ρ_e 235 and displayed completely in two dimensions. Emissions mapping to radial distances less 236 than that of SMO originate at lower latitudes than the SMO, as is the case particularly 237 near dusk in Figure 1. The binned distributions of auroral brightness and number of 238 observations per bin are shown in full in Figure 2; to display these distributions, which 239 are binned in three-dimensional, each panel in Figure 2 represents the two-dimensional 240 distribution with respect to MLT and ρ_e corresponding to a single solar CML bin. 241

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2.2 Galileo PLS Measurements

Plasma parameters derived from the numerical moments of Galileo PLS real-time 243 science data were obtained, as calculated by Frank et al. (2023). The *Galileo* spacecraft's 244 native Inertial Rotor Coordinate (IRC) system, a despun coordinate system based on 245 the spacecraft's geometry, is complex (Bagenal et al., 2016) and has not been fully im-246 plemented into SPICE (Acton et al., 2018), due in part to the Galileo spacecraft her-247 itage predating the SPICE toolkit. SPICE ephemerides for the *Galileo* spacecraft po-248 sition are available for all 6751 moments; spacecraft pointing information is only avail-249 able for 4897 of those 6751. So that the full set of moments can be used, the plasma flow 250



Figure 2. Two-dimensional distributions of the (a,c) auroral brightness and the (b, d) number of observations for both the (a, b) northern and the (c, d) southern hemispheres, with colors for each MLT- ρ_e bin corresponding to the colorbars to the right of each set of panels. Each distribution is labeled with the range of solar CMLs it spans; solar CML ranges for which there are no observations were excluded. In the sample analyzed here, it is evident that the northern hemisphere is typically brighter than the southern and that dusk is typically brighter than dawn.



Figure 3. Plots illustrating *Galileo* PLS coverage of the magnetosphere. Plot (a) shows all 34 *Galileo* orbits projected into Jupiter's equatorial plane in the Jupiter-Despun-Sun (JSS) reference frame, with the region spanning $\pm 30R_J$ in both dimensions highlighted in yellow. (b) A zoomed-in view of the highlighted region in (a), with individual *Galileo* PLS plasma flow speed measurements overplotted as points, colored according to MLT sector: dawn $(03 \le MLT < 09)$ in orange, noon $(09 \le MLT < 15)$ in yellow, dusk $(15 \le MLT < 21)$ in blue, and midnight $(00 \le MLT < 03; 21 \le MLT < 24)$ in purple. (c) A histogram of the number of *Galileo* PLS plasma flow speed measurements in each hour-wide MLT bin. The abundance of dawn and dusk observations, compared to those near noon and particularly near midnight, is evident.

speed is estimated as the root-sum-square of all the velocity components, as the azmiuthal component of the plasma velocity is expected to be much larger than the radial
and polar components.

These numerical moments span 31 of Galileo's 34 orbits, and cover a combined 129 254 days. The plasma parameters span $10R_J \leq \rho_e \leq 30R_J$ within $\sim 1 - 2R_J$ of the equa-255 torial plane, with larger distances from the equatorial plane corresponding to larger ra-256 dial distances. These parameters cover all local times and SIII longitudes, with a bias 257 in local time sampling towards dawn and dusk. Figure 3 illustrates the coverage of the 258 numerical moments relative to *Galileo*'s full orbit and shows this bias. Figures 3a and 259 3b are plotted in the Jupiter-De-Spun-Sun (JSS) reference frame, which is defined to have 260 \hat{Z} aligned with Jupiter's rotational axis, the Sun located in the $\hat{X} - \hat{Z}$ plane, and \hat{Y} com-261 pleting the right-hand orthogonal set. The average plasma corotation rate (R_C) was cal-262 culated for bins spanning 1 hour in MLT and 2 R_J in ρ_e ; as the middle magnetosphere 263 is dominated by magnetic local time effects rather than longitudinal effects (Vogt et al., 264 2011; Ray et al., 2014), the *Galileo* data were not binned by the solar CML of the planet. 265 Binning of the plasma parameters was performed by averaging with weights proportional 266 to the inverse of the parameter variance to be representative of the time-averaged MI-267 coupled system. 268

269 270 The plasma corotation rate R_C is defined as

$$R_C = \frac{v_{flow}}{\rho_e \Omega_J} = \frac{\omega_{flow}}{\Omega_J} \tag{1}$$

where v_{flow} is the calculated linear plasma flow velocity from the *Galileo* PLS data, ω_{flow} is the angular plasma flow velocity ($\omega_{flow} = v_{flow}/\rho_e$), and Ω_J is the angular velocity at which Jupiter rotates ($1.76 \times 10^{-4} \text{ rad s}^{-1}$). R_C is averaged in each bin rather than v_{flow} to account for the expected inverse relationship between equatorial distance ρ_e and v_{flow} . When $v_{flow} = \rho_e \Omega_J$, the plasma is rigidly corotating with the planet and $R_C = 1$. In turn, when $v_{flow} = 0$ then the plasma is fixed with respect to the Sun-



Figure 4. Two-dimensional distributions of the (a) corotation rate (R_C) of the equatorial plasma from *Galileo* PLS moments from Equation 1 and the (b) number of moments. The moments were not binned with respect to solar CML, as the middle magnetosphere is expected to vary primarily in MLT.

Jupiter geometry, or effectively fixed in MLT, and $R_C = 0$. The full set of 6751 plasma parameters used from *Galileo* PLS are summarized in Figure 4, which shows the twodimensional distributions of the corotation rate R_C and the number of moments N with respect to MLT and ρ_e .

281 3 Analysis

The field-aligned current per radian of azimuth, $I_{||}$, in the coupled MI system driving Jupiter's main emission near the ionosphere can be found as

$$I_{||} = -2 \int_{0}^{\rho_{e}} j_{z} \rho_{e}' \, d\rho_{e}' \tag{2}$$

$$=4\Sigma_P^*\Omega_J(1-R_c)F_e\tag{3}$$

adapted from Equation 16 in Cowley and Bunce (2001). Here j_z is the field-aligned cur-282 rent density flowing out of the current sheet lying in the middle magnetosphere's equa-283 torial region, Σ_P^* is the height-integrated effective Pedersen conductance, $\Omega_J = 1.76 \times 10^{-4}$ rad s⁻¹ and R_C are the angular velocity and magnetospheric plasma corotation rates 284 285 defined previously, and F_e is the equatorial flux function, a function which maps the au-286 roral ionosphere to the equatorial middle magnetosphere along contours of constant mag-287 netic flux. The field-aligned current per radian of azimuth $I_{||}$ can be calculated from the 288 auroral brightness observed with HST using Equation 2 and from the plasma flow speed 289 derived from *Galileo* PLS using Equation 3, as will be discussed in Sections 3.1 and 3.2, 290 respectively. 291

3.1 Field-aligned currents from HST observations

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The brightness of the ME aurorae observed with HST is directly proportional to the precipitated energy flux of auroral electrons E_f incident on the atmosphere, with a conversion factor of 10 kR per 1 mW m⁻² (Gustin et al., 2012; Nichols & Cowley, 2022). This energy flux E_f is in turn related to the field-aligned current density just above the auroral ionosphere j_{\parallel} as

$$j_{||} = j_{||,0} \left(\pm \sqrt{2 \frac{E_f}{E_{f,0}}} - 1 \right)$$
(4)

where $j_{\parallel,0}$ is the maximum field-aligned current density above the ionosphere and $E_{f,0}$ 293 is the maximum precipitated energy flux of auroral electrons, both for the case of an ab-294 sence of field-aligned potentials. Equation 4 is derived by assuming the minimum nec-295 essary field-aligned potentials for currents to flow into the ionosphere. The maximum 296 energy flux in the absence of field-aligned potentials is $E_{f,0} = 2N \sqrt{W_{th}/2\pi m_e W_{th}}$ (Equa-297 tion 37 in Cowley and Bunce (2001)), which is a number flux of electrons $(2N\sqrt{W_{th}/2\pi m_e})$ 298 multiplied by a characteristic energy (W_{th}) . $E_{f,0}$ can therefore be estimated by measur-200 able physical parameters; here, $N = 0.018 \text{ cm}^{-3}$ (Bagenal et al., 2016; Huscher et al., 300 2021) and $W_{th} = 5$ keV (Allegrini et al., 2021) are used. Similarly, the maximum field-301 aligned current density just above the ionosphere in the absence of field-aligned poten-302 tials is $j_{\parallel,0} = eN\sqrt{W_{th}/2\pi m_e}$, the number flux of electrons multiplied by e, the ele-303 mentary charge (Equation 28 in Cowley and Bunce (2001)). 304

The quantity j/B is constant along a magnetic field line provided there are no field-305 perpendicular currents intersecting the field line outside of the equatorial and ionospheric 306 regions (Cowley & Bunce, 2001), so $j_{||}$ can be written as $j_z B_i/B_e$, where B_i and B_e are 307 the strengths of the magnetic field along the field line in the ionosphere and the current 308 sheet in the equatorial plane, respectively. The magnetic field strength in the equato-309 rial plane of the magnetosphere B_e , is calculated from the form provided in Vogt et al. 310 (2011), which is itself a fit to in-situ magnetic field measurements from *Pioneer 10*, *Pi*-311 oneer 11, Voyager 1, Voyager 2, Ulysses, and Galileo spanning 20-120R_J. The mag-312 netic field strength in the ionosphere was found using the internal magnetic field model 313 based on Juno's first 33 orbits of Connerney et al. (2022)(henceforth, JRM33), calcu-314 lated to order 13 using the code provided by Wilson et al. (2023), and assuming an al-315 titude of $1R_J$. The magnetic field function of Vogt et al. (2011) is more appropriate for 316 B_e than the more recent JRM33 model as it captures the significant variation of the mid-317 dle and outer magnetosphere with MLT; beyond $10R_{\rm J}$, the higher order terms in the JRM33 318 model become negligible and the resulting field is very nearly dipolar and azimuthally 319 symmetric. 320

Equation 4 can thus be substituted into Equation 2 for j_z to give

$$I_{||} = -2 \int_{0}^{\rho_{e}} j_{||,0} \frac{B_{e}}{B_{i}} \left(\pm \sqrt{2 \frac{E_{f}}{E_{f,0}} - 1} \right) \rho_{e}' \, d\rho_{e}' \tag{5}$$

which can be used to calculate the field-aligned current per radian of azimuth $I_{||}$ cor-321 responding to a given auroral brightness. Evaluation of Equation 5 requires and inte-322 grable auroral electron energy flux $E_f(\rho'_e)$, which in turn requires a function of the au-323 roral brightness over equatorial distance. The variation of the auroral brightness with 324 equatorial distance illustrated in Figure 2 does not represent this function directly. In-325 stead, these distributions show the typical values of the observed ME when the ME maps 326 to a given location in MLT- ρ_e space, which in turn represents the maximum of the field-327 aligned current density j_z for a given span of solar CML. An integrable radial distribu-328 tion of $E_f(\rho'_e)$ is therefore approximated as a Gaussian having a peak value of E_f , a cen-329 ter defined by the corresponding radial bin, and a width defined by the angular width 330 of the ME ($\delta \theta$) magnetospherically mapped to a radial width ($\delta \rho_e$). The resulting ra-331 dial distributions are then numerically integrated from 0 out to the corresponding ρ_e value. 332



Figure 5. Two-dimensional distributions of the integrated field-aligned current per radian of azimuth ($I_{||}$ calculated from Equation 5 for the (a) northern and (b) southern hemispheres, with colors for each MLT- ρ_e bin corresponding to the colorbars to the right. Each distribution is labeled with the range of solar CMLs it covers. Generally, stronger currents are seen to occur at dusk rather than dawn, and when the magnetosphere is more perturbed (i.e., when the ME maps to more distant regions of the magnetosphere).



Figure 6. Two-dimensional distribution of the quantity $I_{||}/\Sigma_P^*$ derived from the *Galileo* PLS moments using Equation 6, with colors in each MLT- ρ_e bin corresponding to the colorbar to the right. Generally, $I_{||}/\Sigma_P^*$ is seen to be smaller at dawn than at dusk.

The resulting values of $I_{||}$ we report are thus average field-aligned currents per radian 333 of azimuth entering the ionosphere at the ME, when the location of the ME maps to the 334 current sheet at the location specified by the corresponding bin. The distributions of $I_{||}$ 335 with MLT, ρ_e , and solar CML in Figure 5 thus illustrate various independent MI cou-336 pling configurations rather than multiple samples of the same configuration. To clarify 337 further, the distributions of $I_{||}$ calculated here are not expected to increase monotoni-338 cally with equatorial distance ρ_e , even though the integral of $F_e(\rho'_e)$ would, for the same 339 reasons that the ME brightness does not increase monotonically with ρ_e in Figure 2. 340

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3.2 Field-aligned currents from Galileo-PLS data

Returning to Equation 3 and rearranging, the total field-aligned current per radian of azimuth $I_{||}$ flowing into the ionosphere divided by the effective, height-integrated Pedersen conductance Σ_P^* of the ionosphere, can be found as

$$\frac{I_{||}}{\Sigma_P^*} = 4\Omega_J (1 - R_c) F_e \tag{6}$$

The height-integrated effective Pedersen conductance Σ_P^* is the sum of all conductance 342 terms and is reduced from the true value, Σ_P , by a factor of (1-k) to account for the 343 slippage in the ion-neutral coupling in the ionosphere. The values of k range from 0 < 1344 k < 1, with k = 0 corresponding to no slippage of the neutral atmosphere relative to 345 the planet's rigid rotation rate and $k \approx 1$ corresponding to maximal slippage (Huang 346 & Hill, 1989; Nichols & Cowley, 2003). The equatorial flux F_e , which relates locations 347 in the ionosphere to conjugate points in the current sheet in the equatorial plane of the 348 magnetosphere along contours of constant magnetic flux, is a function of both MLT and 349 ρ_e and is calculated using the form provided by Ray et al. (2014). This description of 350 $F_e(MLT, \rho_e)$ is based on a slightly modified version of the empirical magnetic field model 351 used to map HST observations into the equatorial magnetospheric plane (Vogt et al., 2011). 352 The differences between this and the unmodified empirical magnetic field model are great-353 est near the planet; the two descriptions agree throughout the middle magnetosphere where 354 MI coupling currents flow, ensuring consistency between the values derived from *Galileo* 355 PLS and HST observations. 356

The quantity I_{\parallel}/Σ_P^* can thus be solved for using *Galileo* PLS-derived values of the plasma corotation rate R_c and the known form of F_e . This quantity is introduced for convenience and has limited physical meaning, despite having the form of an electric potential. Instead, the quantity $I_{||}/\Sigma_P^*$ groups unknown parameters together, and will allow further exploration of the distribution of Σ_P^* when compared to the values of $I_{||}$ derived from HST observations. Figure 6 shows the distributions of the quantity $I_{||}/\Sigma_P^*$ with MLT and equatorial distance ρ_e .

³⁶⁴ 4 Results and Discussion

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4.1 Azimuthally integrated field-aligned currents

First, we focus on the field-aligned current per radian azimuth $I_{||}$ derived from HST 366 observations, which, unlike the parameter I_{\parallel}/Σ_P^* derived from Galileo measurements, 367 is representative of the field-aligned auroral currents flowing in Jupiter's coupled MI sys-368 tem without any further assumptions about the ionospheric Pedersen conductance. The 369 northern ME is found to have a median current per radian of azimuth of $I_{||} = 9.54^{+11.5}_{-6.35}$ 370 MA rad⁻¹, while the southern ME has a median current per radian of azimuth of $I_{||} =$ 371 $10.6^{+11.1}_{-6.11}$ MA rad⁻¹. These median values are found using a Monte Carlo bootstrap anal-372 ysis with lognormal error perturbation (henceforth just "medians"), in order to better 373 account for the measurement errors in the non-Gaussian distribution of currents (Curran, 374 2014). Upper and lower errors correspond to the 84^{th} and 16^{th} percentiles, respectively, 375 to approximate 1σ errors. These median currents are in very good agreement with the 376 currents calculated from Juno magnetometer measurements, both lying within the $\sim 1-$ 377 27 MA rad⁻¹ range of $I_{||}$ (Nichols & Cowley, 2022) and reproducing the magnitude, af-378 ter accounting for integration over azimuth, and North-South asymmetry previously mea-379 sured (Kotsiaros et al., 2019). 380

4.2 Effective Pedersen conductance

The effective Pedersen conductance (Σ_P^*) can be calculated by dividing the field-382 aligned current per radian of azimuth derived from HST measurements $(I_{||})$ by the quan-383 tity derived from Galileo PLS moments $(I_{\parallel}/\Sigma_P^*)$. Figure 7 shows distributions of this 38/ calculated effective Pedersen conductance for the northern and southern hemispheres; these plots are limited to $10 < \rho_e \leq 30 R_J$ due to the coverage of the *Galileo* PLS moments. The binned distributions of $I_{||}/\Sigma_{P}^{*}$ are assumed to be the same at all solar CML in this 387 analysis. We find 95% of conductances lie in the range $0.03 < \Sigma_P^* < 1.79$ mho in the north 388 with a median of $\Sigma_P^* = 0.14_{-0.09}^{+0.31}$ mho and $0.02 < \Sigma_P^* < 2.26$ mho in the south with a median of $\Sigma_P^* = 0.14_{-0.09}^{+0.34}$ mho, with errors corresponding to the 16th and 84th percentiles. 389 390 These averages are comparable to both theoretical estimates (Millward et al., 2002, 2005) 391 and recent estimates made using Juno ultraviolet spectrograph (UVS) measurements and 392 ionospheric modeling (Gérard et al., 2020, 2021) of $\Sigma_P \approx 0.5$, considering that these 393 reported values are not reduced by the (1-k) factor. For typical values of $k \approx 0.4$ – 394 0.7 (Millward et al., 2005), the novel method used here to calculate the conductance of 395 the auroral ionosphere is in good agreement with literature values. 396

For clarity, Figure 8 shows the same data as Figure 7, but with the medians and 397 the $84^{th}/16^{th}$ percentile errors of the effective Pedersen conductance in each bin plot-398 ted. By comparison to the average values and errors for each hemisphere overall, the vari-399 ations in conductance with respect to each binning parameter can be seen. Figures 8c 400 and 8f show that Σ_P^* varies minimally with solar CML. Figures 8b and 8e show that the 401 effective Pedersen conductance is generally higher at smaller radial values, correspond-402 ing to higher field-aligned currents when the magnetosphere is in a disturbed enough state 403 for the ME to map to these distances. The conductance thus increases with current, as 404 expected (Nichols & Cowley, 2004). The bin-to-bin variation is greatest when the con-405 ductance is interpreted as a function of MLT, as shown in Figures 8a and 8d. This significant variation in effective conductance with MLT is more likely than the variations 407 with equatorial distance or solar CML to be related to the local time asymmetries in the 408 appearance, distribution, and motion of ME aurorae. Both hemispheres display peaks 409



Figure 7. Two-dimensional distributions of the effective Pedersen conductance Σ_P^* for the (a) northern and (b) southern hemispheres, with the color of each MLT- ρ_e bin corresponding to the colorbars to the right. The effective Pedersen conductance is only calculated where both HST-derived and *Galileo* PLS-derived data are present. Generally, the conductance is greatest at smaller radial distances and nearer dawn.

⁴¹⁰ in the effective conductance between 7-8, 12-13, and 14-15 MLT. It is worth not-⁴¹¹ ing that, without the limb-brightening correction applied to HST-observed auroral bright-⁴¹² ness, derived field-aligned currents would be increased more near dawn and dusk than ⁴¹³ near noon, and Σ_P^* would increase proportionally. The overestimation of the limb-brightening ⁴¹⁴ correction factors thus results in an underestimation of the conductance near the planet's ⁴¹⁵ limbs at dawn and dusk, and a more accurate model of Jupiter's limb-brightening would ⁴¹⁶ heighten the peak in Σ_P^* between 7-8 MLT further than the others.

Figure 9 shows the complete conductance distributions mapped onto Jupiter's au-417 roral ionosphere for each solar CML bin, allowing the variation in Σ_P^* with local time 418 and location relative to the SMO to be visualized. The generally increased effective Ped-419 ersen conductance near local dawn, located to the left of each frame in Figure 9, is ev-420 ident. The smooth decrease in Σ_P^* with increasing ρ_e can be seen as a decrease in Σ_P^* 421 with increasing latitude, particularly in the noon and dusk sectors, in Figure 9a. The 422 same trend is not seen in Figure 9b, as the middle magnetosphere maps to a smaller range 423 of latitudes in the southern ME than in the northern ME. 424

From the derived distributions of Σ_P^* alone, we cannot determine the cause of the variation of the conductance with MLT. It is of interest, however, that the effective Pedersen conductance peaks in the late-dawn (7 - 8 MLT) and noon (12 - 13 MLT) regions are generally colocated with known subcorotating emission features within the ME: the dawn storms and associated, less bright subcorotating emission features in the post-



Figure 8. Plots showing the trends in the median effective Pedersen conductance Σ_P^* with MLT (a, d), ρ_e (b, e), and solar CML (c, f) for the northern (a, b, c; blue circles) and southern (d, e, f; red triangles) hemisphere ME. The conductance varies widely with MLT and insignificantly with solar CML.

dawn region (Rutala et al., 2022) and the noon discontinuity and auroral spot near noon
(Radioti et al., 2008; Palmaerts et al., 2014).

The co-occurrence of increased ionospheric conductance and subcorotating auro-432 ral features within the ME was hypothesized by Rutala et al. (2022) as an explanation 433 of subcorotational behavior near dawn. The basic premise is that, if the ionospheric con-434 ductance is locally increased for a reason unrelated to MI-coupling currents, the MI-coupling 435 currents will increase in magnitude due to the heightened conductance, accelerating mag-436 netospheric plasma up to the corotation rate of the planet; as the magnetosphere gen-437 erally compresses from dawn through noon, the linear velocity of the recently-accelerated 438 magnetospheric plasma would exceed the local angular corotational velocity as the sys-439 tem rotates, thus reducing or reversing the field-aligned currents. In the ionosphere, this 440 would appear as a bright auroral form associated with the increased currents which ends 441 abruptly as the currents reverse, thus appearing fixed in local time. This picture meshes 442 well with the noon ME discontinuity observed by Radioti et al. (2008), which is expected 443 to be associated with reduced or reversed field-aligned currents. The secondary peak in 444 Σ_{P}^{*} near noon may be associated with the subcorotational noon auroral spot (Palmaerts 445 et al., 2014), as following noon the magnetosphere expands again, thus requiring increased 446 field-aligned currents to bring plasma up to local corotational velocity. 447

This second peak in Σ_P^* near 12 MLT may instead be caused by increased field-448 aligned currents caused by shearing motions of magnetospheric plasma, as modeled by 449 Chané et al. (2018). Generally, as an increase in the field-aligned currents will cause an 450 increase in the effective Pedersen conductance, we cannot distinguish between cause and 451 effect with this data set: high currents could cause increased conductance, or heightened 452 conductance may drive increased currents. It is of note that the conductance distribu-453 tions found in Figure 8 are more similar to the modeled conductance distribution in LT 454 found by Tao et al. (2010) than to the distributions in solar CML found by Gérard et 455 al. (2020, 2021). In the latter case, the differences may in part be explained by the dif-456 ference in observational integration time. Images from HST span non-overlapping 30-457 100 s exposures while spectral images from Juno were integrated over 20-50 min (Gérard 458 et al., 2020, 2021), which would introduce more smoothing into the Juno UVS based maps 459 than is present in this analysis. The similarity in form between the Σ_P^* distributions found 460 here and those of Tao et al. (2010) may indicate a relationship between heightened dawn 461



Figure 9. Polar, orthographic views of Jupiter's north auroral region, with the derived Σ_P^* distributions shown mapped onto the planet by mapping MLT and ρ_e onto λ_{III} and ϕ . Each frame corresponds to one solar CML bin with the mean solar CML, and hence noon local time, located at the bottom of the image. The SMO is shown by a red-dashed line, and λ_{III} and ϕ graticules are shown in yellow. Values of Σ_P^* have been log-scaled and correspond to the colorbar to the right. The increased conductance near dawn, toward the left side of each frame, can be seen, as can the increased conductance at lower latitudes (mapping to smaller ρ_e).

sector conductance and incident solar extreme ultraviolet (EUV) photons, which increase
 the Pedersen conductance by ionizing the ionosphere.

464 5 Conclusions

We have outlined a novel method for deriving values of the effective Pedersen con-465 ductance Σ_{P}^{*} of Jupiter's ME auroral ionosphere by combining remote observations of 466 the Jovian ME and in-situ observations of the angular velocity, or corotation rate, of mid-467 dle magnetospheric plasma. This method has been developed from the theoretical un-468 derstanding of MI coupling at Jupiter, which links the field-aligned currents entering the 469 ionosphere, estimated from the auroral brightness measured with HST, to the motion 470 of middle magnetospheric plasma, calculated by moment analysis of *Galileo* PLS mea-471 surements. Equivalent regions of the auroral ionosphere and equatorial magnetosphere 472 are found using magnetic flux equivalence mapping. The non-overlapping 288 HST ob-473 servations and 6751 Galileo measurements used in this analysis are taken to be repre-474 sentative of the time-averaged Jupiter system. 475

From the HST observations, we find field-aligned currents entering the ionosphere 476 of $I_{||} = 9.54^{+11.5}_{-6.35}$ MA rad⁻¹ and $I_{||} = 10.6^{+11.1}_{-6.11}$ MA rad⁻¹, corresponding to the northern and southern ME, respectively, in agreement with recent Juno-based measurements 477 478 (Kotsiaros et al., 2019; Nichols & Cowley, 2022) and theoretical estimates (Hill, 2001; 479 Cowley & Bunce, 2001). Combining these values with the parameter $I_{\parallel}/\Sigma_{P}^{*}$ derived from 480 in-situ Galileo PLS measurements, we find the effective Pedersen conductance Σ_P^* , re-481 duced from the true Pedersen conductance by a factor of $1 - k \approx 0.5$. Σ_P^* ranges be-482 tween $0.03 < \Sigma_P^* < 1.79$ mho in the north and $0.02 < \Sigma_P^* < 2.26$ mho in the south, with typical values of $\Sigma_P^* = 0.14^{+0.31}_{-0.08}$ mho and $\Sigma_P^* = 0.14^{+0.34}_{-0.09}$ mho in the northern and 483 484 southern ME, respectively. These typical values are consistent with theoretical and modeled values (Millward et al., 2002, 2005; Gérard et al., 2020, 2021), but the distributions 486 of Σ_P^* we find reveal that it varies primarily in MLT, rather than solar CML. This anal-487 ysis indicates that the field-aligned currents derived from MI coupling theory, which have 488 historically been used to explain Jupiter's ME, adequately describe the relationship be-489 tween ME auroral brightness and the motion of middle magnetospheric plasma. Further, 490 the heightened effective Pedersen conductance near MLTs of 07-08 and 12-13 MLT 491 we find are approximately co-located with auroral features in the ME with subcorota-492 tional motions (Rutala et al., 2022; Radioti et al., 2008; Palmaerts et al., 2014). The re-493 sults we present are compatible with the theory that solar EUV ionization of the auro-494 ral ionosphere is key to controlling the motions of subcorotational auroral features in the 495 dawn sector. We cannot, however, distinguish between this case and the case of otherwise-496 increased dawn currents causing locally elevated conductances. Breaking the observa-497 tional degeneracy between these cases should be done with comparisons of the distribu-498 tions found here to models of the field-aligned currents flowing in the MI coupling sys-499 tem under varying ionospheric conductance conditions. 500

Open Research 501

All Hubble Space Telescope observations used in this analysis are available at the 502 Mikulski Archive for Space Telescopes hosted by the Space Telescope Science Institute. 503 and have been collected into a single dataset for ease of access (Rutala, 2022). All Galileo 504 PLS real-time-science data are available through the Planetary Plasma Interaction (PPI) 505 node of the Planetary Data System (PDS) (Frank et al., 2023). This research made use 506 of the ionosphere-magnetosphere mapping code of Vogt et al. (2011) and the internal mag-507 netic field model of Connerney et al. (2022) as made available by Wilson et al. (2023) 508 509 to allow comparison between in-situ and remote measurements.

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Variation in the Pedersen Conductance near Jupiter's Main Emission Aurora: Comparison of Hubble Space Telescope and Galileo Measurements

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Key Points:

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10	•	The effective ionospheric Pedersen conductance in Jupiter's main emission auro-
11		ral region is derived from remote and in-situ measurements.
12	•	Field-aligned auroral currents of $\sim 10 \text{ MA rad}^{-1}$ and effective Pedersen conduc-
13		tances of ~ 0.14 mho are derived, consistent with past research.
14	•	The effective Pedersen conductance varies primarily in magnetic local time, and
15		may explain the enigmatic motions of some auroral forms.

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16 Abstract

We present the first large-scale statistical survey of the Jovian main emission (ME) to 17 map auroral properties from their ionospheric locations out into the equatorial plane of 18 the magnetosphere, where they are compared directly to in-situ spacecraft measurements. 19 We use magnetosphere-ionosphere (MI) coupling theory to calculate currents from the 20 auroral brightness as measured with the Hubble Space Telescope and from plasma flow 21 speeds measured in-situ with the *Galileo* spacecraft. The effective Pedersen conductance 22 of the ionosphere (Σ_P^*) remains a free parameter in this comparison. We first show that 23 the field-aligned currents per radian of azimuth calculated from the auroral observations, 24 found to be $I_{||} = 9.54^{+11.5}_{-6.35}$ MA rad⁻¹ and $I_{||} = 10.64^{+11.1}_{-6.11}$ MA rad⁻¹ in the north and south, respectively, are consistent with previous results. Then, we calculate the Peder-25 26 sen conductance from the combined datasets, and find it ranges from $0.02 < \Sigma_P^* < 2.26$ 27 mho overall with averages of $0.14^{+0.31}_{-0.08}$ mho in the north and $0.14^{+0.26}_{-0.09}$ mho in the south. 28 Taking the currents and effective Pedersen conductance together, we find that the av-29 erage ME intensity and plasma flow speed in the middle magnetosphere (10-30 R_J) are 30 broadly consistent with one another under MI coupling theory. We find evidence for peaks 31 in the distribution of Σ_{P}^{*} near 7, 12, and 14 hours magnetic local time (MLT). This vari-32 ation in Pedersen conductance with MLT may indicate the importance of conductance 33 in modulating MLT- and local-time-asymmetries in the ME, including the apparent sub-34 corotation of some auroral features within the ME. 35

³⁶ Plain Language Summary

The brightest part of Jupiter's aurorae- the main emission- forms arcs of sheet-37 like lights surrounding both magnetic poles, similar to the Earth's aurorae. At both plan-38 ets, these lights are caused by charged particles flowing into the planet's atmosphere, where 39 they collide with gases and glow. At Jupiter, these particles are electrons which flow in 40 electrical currents connecting the planet to the charged-particle-filled space surround-41 ing it. Here, we use Hubble Space Telescope images of Jupiter's aurorae spanning a decade 42 to build up an average picture of the brightness and location of this main emission. The 43 brightness is related to the energy of the electrons, which in turn is related to the strength 44 of electrical currents flowing near the planet. We then use particle measurements made 45 by the Galileo spacecraft in orbit around Jupiter to make an average picture of these par-46 ticle's as they move around Jupiter. These speeds are related to the same electrical cur-47 rents, but include an electrical conductivity term describing how easily currents flow through 48 Jupiter's auroral atmosphere. We combine all these measurements to calculate the con-49 ductivity, and present results which are consistent with expectations but which fluctu-50 ate more quickly than expected in parts of the main emission. 51

52 1 Introduction

Jupiter's ultraviolet (UV) auroral main emission (ME), typically the most power-53 ful component of the planet's large-scale auroral regions, takes the form of a partially-54 closed oval of auroral emission surrounding each of the planet's magnetic poles. The Jo-55 vian aurorae are detectable at all local times (LT) including on the planet's dayside(Clarke 56 et al., 2004; Bonfond et al., 2017), where they are significantly brighter than Jupiter's 57 surface UV emission (Gustin et al., 2012) and can thus be observed routinely with the 58 Hubble Space Telescope (HST). In the southern hemisphere, the ME forms a nearly cir-59 cular curtain of light; however, the presence of multiple significant non-dipolar magnetic 60 field components in the northern hemisphere complicates the structure, resulting in a 61 characteristic 'kidney bean' shape (Grodent et al., 2008; Connerney et al., 2022), as shown 62 by the HST observation and statistically-averaged reference main oval ('statistical main 63 oval', or SMO) in Figure 1a. 64

The ME has historically been thought to originate from the magnetosphere-ionosphere 65 (MI) coupling currents flowing in the Jovian middle magnetosphere, radially outward in 66 the equatorial plasma disc, equatorward in the ionosphere, and along magnetic field lines 67 between (Hill, 2001; Cowley & Bunce, 2001; Nichols & Cowley, 2003, 2004, 2005; Ray 68 et al., 2010, 2014; Smith & Aylward, 2009; Tao et al., 2009). This current system arises 69 from the azimuthal distortion (or 'bendback') of the field caused by the planet's reser-70 voir of angular momentum opposing the decrease in angular velocity of flux tubes laden 71 with Iogenic plasma as they diffuse radially outward . In the absence of torques, these 72 diffusing flux tubes would tend to conserve angular momentum, resulting in a decrease 73 in the angular velocity proportional to r^{-2} . The resultant lag in the flux tubes corre-74 sponds to an azimuthal bendback in the magnetic field structure and thus a loop of field-75 aligned current which acts to partially enforce the corotation of the plasma composing 76 the plasma disk by exerting a $\mathbf{J} \times \mathbf{B}$ force in the direction of corotation. The strongest 77 field-aligned currents occur near where rigid corotation breaks down (Hill, 1979; Nichols 78 & Cowley, 2004). The ME current system is characterized primarily by the rapid ro-79 tation and strength of Jupiter's magnetic field, rather than by solar influence as is the 80 case in the Earth's own magnetosphere and auroral ovals (Cowley & Bunce, 2001; South-81 wood & Kivelson, 2001), though solar wind influence is not completely absent (Kita et 82 al., 2019; Nichols et al., 2017). These MI-coupling currents and the associated ME ovals 83 are thus always present, owing to the continuous production of Iogenic plasma and dif-84 fusion of this plasma outward through the magnetosphere. 85

The production and diffusion of Iogenic plasma is not constant and the Jovian mag-86 netosphere is varies in System III (SIII) magnetic longitude (λ_{III}), local time (LT), and 87 magnetic local time (MLT). This results in various asymmetries in the brightness, shape, 88 distribution, and dynamics of auroral forms within the ME oval. The southern ME is 89 brighter on average than the northern (Gérard et al., 2013) and the dusk side of the ME 90 is brighter on average than dawn, an effect which is amplified in the brighter southern 91 hemisphere (Bonfond et al., 2015). On occasions where the dawn side is brighter than 92 dusk, an exceptionally bright auroral feature – a dawn storm, perhaps – is typically lo-93 cated on the dawn ME (Gérard, Grodent, et al., 1994; Bonfond et al., 2021; Rutala et 94 al., 2022). While the locations of the ME remain fixed in SIII longitude and latitude (Clarke 95 et al., 2004; Gérard, Dols, et al., 1994; Grodent et al., 2003), auroral features on the ME 96 may subcorotate, lagging behind the rigid corotation rate of the planet. Subcorotation 97 occurs more often in the dawn sector than the noon and dusk sectors (Rutala et al., 2022). 98 an effect which appears to be separate from the appearance of bright dawn storms. Ad-99 ditional subcorotating auroral forms, the ME auroral discontinuity (Radioti et al., 2008) 100 and small-scale brightening (Palmaerts et al., 2014) are observed localized near noon. 101 The dusk side of the ME as viewed from the Earth is typically wider and more diffuse 102 than near dawn (Gérard, Dols, et al., 1994); this asymmetry is larger in the northern hemi-103 sphere, where the northern magnetic anomaly is typically located in remote observations 104 (Grodent et al., 2008). This asymmetry was originally considered to be a variation in 105 local time (Caldwell et al., 1992), before improved HST observations made it appear to 106 be a variation in SIII longitude (Gérard, Dols, et al., 1994). Recent Juno observations 107 of the ME oval morphology indicate that this asymmetry may vary in a more complex 108 way, dependent on both local time and SIII longitude (Greathouse et al., 2021). 109

These phenomena have generally been thought to arise from deviations from the 110 ideal axisymmetric MI-coupling theory previously discussed. However, predictions of 111 this theory are not always in accordance with observations, raising the possibility that 112 the MI-coupling theory itself only partially describes the generation of the ME oval at 113 Jupiter (Bonfond et al., 2020). Mean field-aligned MI-coupling currents of 58 MA and 114 24 MA in the southern and northern ME regions, respectively, have been derived from 115 Juno measurements, reflecting the observed north-south brightness asymmetry of the 116 ME ovals (Kotsiaros et al., 2019). These currents appear in primarily longitudinal, though 117 variable, sheets in keeping with the schematic picture of MI coupling theory. Further Juno 118

measurements have found that the field lines associated with ME aurorae host precip-119 itating electrons, as required to drive field-aligned currents, along with bi-directional elec-120 tron distributions (Mauk et al., 2017, 2018), suggesting that additional auroral emission 121 zones, co-located or nearly co-located with the ME, may be driven by acceleration pro-122 cesses other than field-aligned potentials (Mauk et al., 2020). The measured bi-directional 123 electron distributions may, however, be a secondary effect, driven by the flow of intense 124 field-aligned currents (Nichols & Cowley, 2022). The equatorial radial currents derived 125 from Juno magnetometer measurements are highly correlated with simultaneous HST 126 observations of the dawnside ME auroral intensity (Nichols & Cowley, 2022). On large 127 scales, the MI-coupling theory still explains the bulk of the observed variation in ME au-128 roral brightness, including during short-term enhancements (Nichols et al., 2020). 129

A further discrepancy between the modeled and observed auroral MI-coupling sys-130 tem at Jupiter lies in the auroral brightness asymmetry across the dayside ME. While 131 the dusk side of the ME oval is typically observed to be brighter than the dawn side (Bonfond 132 et al., 2015), models predict that this asymmetry should be reversed owing to the larger 133 field bend-back in the dawn sector (Ray et al., 2014). Field bend-back is strongly cor-134 related with ME auroral brightness, particularly near dawn (Nichols & Cowley, 2022). 135 Field bend-back is caused by angular plasma flow speeds in the middle magnetosphere 136 slower than the rotation rate of the planet, or subcorotation relative to the planet's ro-137 tation, so in considering only the quasi-steady-state MI coupling current system, an an-138 ticorrelation between the degree of field bend-back and plasma angular velocity is ex-139 pected (Bonfond et al., 2020). A partial ring current, spanning the nightside middle mag-140 netosphere with a source near dusk and a sink near dawn (Walker & Ogino, 2003) may 141 ease this tension if the ring current closes along field-aligned currents, decreasing the ef-142 fective field-aligned currents near dawn and increasing them near dusk (Bonfond et al., 143 2015). On top of this effect, careful consideration is required to relate instantaneous, in-144 situ measurements of plasma velocity to the measurement of magnetic field bend-back 145 in a dynamic region of the magnetosphere such as the dawn sector. The anticorrelation 146 between field bend-back and plasma velocity is only maintained in the quasi-steady-state 147 scenario. If magnetospheric plasma near dawn is rapidly accelerated, the measured plasma 148 velocity may be high despite large degrees of field bend-back, as the plasma and field lines 149 have yet to "catch up" to corotational velocity. This scenario matches observations of 150 both the plasma (Krupp et al., 2001; Bagenal et al., 2016) and the magnetic field (Khurana 151 & Schwarzl, 2005) near dawn. Such a sudden acceleration of the middle magnetospheric 152 plasma may be driven by an equally sudden increase in the conductance of the MI-coupling 153 circuit, as is the case near the dawn terminator where the previously-unlit ionosphere 154 is re-photoionized by solar extreme ultraviolet (EUV) light (Tao et al., 2010). This sce-155 nario has been suggested to explain the apparent subcorotation of some auroral forms 156 relative relative to the SMO in the dawn sector (Rutala et al., 2022), and will be explored 157 here in more detail. 158

Here, we present the first large-scale statistical survey of the typical HST-observed 159 ME brightness, spanning more than 10 years and 200 cumulative hours of exposure time. 160 The ME brightness is mapped from the polar ionosphere out into the magnetospheric 161 equatorial plane and averaged in bins defined by MLT, equatorial radial distance (ρ_e), 162 and the solar central meridian longitude (solar CML), so that variations relative to MLT 163 and λ_{III} can be differentiated. From these binned values, the associated maximum field-164 aligned current density and total currents under MI-coupling theory are derived. We com-165 pare the derived total currents from this novel analysis of HST observations to litera-166 ture values, finding good agreement in scale. These values are then compared to non-167 contemporaneous in-situ Galileo Plasma Science (PLS) measurements of the plasma flow 168 speed and associated field-aligned current density and total current binned in the same 169 way as the HST observations in order to perform a superposed epoch analysis. Finally, 170 we compare the HST- and *Galileo*- derived currents directly, assuming that they fully 171 describe the large-scale, time-averaged state of the MI-coupling system, to derive a dis-172



Figure 1. Plots showing multiple views of Jupiter's northern ME on May 22, 2016 beginning at 18:02:46 UTC, as observed with HST STIS. Panel (a) shows a top-down, polar view of the northern ME, with the statistical main oval (SMO) shown with a red dashed line and λ_{III} and latitude graticules in yellow. Panel (b) shows a labeled keogram, where the observation in (a) is represented in the first (top) row. The values in both (a) and (b) are log-scaled with colors corresponding to the colorbar beneath. Panel (c) depicts the same keogram, but with a limb-brightening correction applied. Panel (d) shows the corrected keogram projected to the magnetospheric equatorial plane as a function of MLT and ρ_e , with the projected SMO corresponding to the first (dashed) and final (dotted) exposures shown in red. The values in both (c) and (d) are log-scaled, with colors corresponding to the separate colorbar beneath.

tribution of the Pedersen conductance in MLT, ρ_e , and solar CML. The resulting conductance distribution is additionally mapped back into the ionosphere. We find that the Pedersen conductance peaks in the dawn sector, and varies primarily in MLT, consistent with controlling the subcorotation of auroral forms in the dawn ME and helping resolve the tension between high degrees of field bend-back and high plasma velocities in the dawn sector.

179 2 Data

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2.1 Hubble Space Telescope Data

Archival observations of Jupiter's ultraviolet (UV) aurorae made with the Advanced Camera for Surveys Solar Blind Channel (ACS/SBC) and Space Telescope Imaging Spectrograph (STIS) on HST were obtained for this study. These observations comprise more than 200 cumulative hours of exposure, and span 2007 and 2016–2019; this large survey is expected to be representative of the general state of Jupiter's main emission aurorae. Further details about this set of observations are presented in Rutala et al. (2022) and references therein.

Time-tagged STIS observations were split into non-overlapping 30s intervals to cre-188 ate images, while the typical ~ 100 s exposures for the ACS observations were unchanged. 189 Images were reduced and projected onto an equirectangular planetocentric grid using the 190 standard procedures in the Boston University HST data reduction pipeline (Clarke et 191 al., 2009; Nichols & Cowley, 2022; Rutala et al., 2022, e.g.); the projection from the HST 192 perspective to an equirectangular grid allows the observations to be viewed from any per-193 spective, as illustrated by the reduced observation mapped to an orthographic polar view 194 in Figure 1a. The factors used to convert the observed auroral brightness from counts/s 195 to kR of unabsorbed H and H_2 emission vary with color ratio (Gustin et al., 2012), which 196 can change rapidly on both small and large scales. Here, we estimate an effective value 197 of the color ratio of 12 in the ME region from Juno ultraviolet spectrograph (UVS) based 198

maps of the color ratio distribution (Gérard et al., 2018). Auroral intensities in the ACS/SBC
images were further multiplied by a factor of 1.4 for those using the F115LP filter and
1.6 for those using the F125LP filter, following recent changes to the SBC absolute flux
calibration (Avila et al., 2019).

In each reduced image, an ME brightness profile is measured as the mean bright-203 ness of the brightest quartile of emission within $\pm 5^{\circ}$ perpendicular to the SMO, as found 204 by Nichols et al. (2009), in steps along the ME. 300 steps evenly spaced in distance along 205 the SMO with dynamic sizes were found to maximize resolution while preventing over-206 lap between pixels sampled by adjacent steps. The extracted brightness profile is stacked 207 into a keogram for each image within the same HST visit, and aligned such that the lo-208 cation along the SMO is measured horizontally and exposure time is measured vertically. 209 Figure 1b shows a keogram created in part from the observation in Figure 1a, with SIII 210 coordinates, distance along the SMO, and MLT all labeled. Limb-brightening correction 211 factors found as the inverse cosine of the view angle (Grodent et al., 2005) were applied 212 to each keogram, the results of which are demonstrated in Figure 1c. The inverse-cosine 213 correction generally overestimates the limb-brightening effect very near the edge of planet's 214 disk as viewed by HST. The effect of this overestimation is partially countered by remov-215 ing all parts of the observations within 10° of the limb; the slight remaining effects of 216 the overestimation will be discussed in the Results. The keogram production process is 217 further discussed in Rutala et al. (2022). 218

In each of the 288 keograms, the auroral brightness (I), local time (LT), latitude 219 (ϕ) , System III longitude (λ_{III}) , and the 1σ width $(\delta\theta)$ of the ME were recorded for ev-220 ery pixel. Pixels were then mapped from λ_{III} and ϕ in the ionosphere to magnetic lo-221 cal time (MLT) and radial distance in the equatorial plane of the mangetosphere (ρ_e) 222 using the magnetic flux equivalence mapping of Vogt et al. (2011). The internal mag-223 netic field for the mapping was specified to be the JRM09 magnetic field model (Connerney 224 et al., 2018) which, over the spatial scales relevant here, is very similar to the more re-225 cent JRM33 model (Connerney et al., 2022). Solar CML values for the mapping were 226 found using ephemerides from the NASA NAIF SPICE toolkit (Acton et al., 2018). The angular width of the ME, $\delta\theta$, was mapped to a radial width, $\delta\rho_e$, in the same manner. 228 The observed and mapped parameters were then binned by 1 hour in MLT, 2 R_J in ρ_e , 229 and 24° in solar CML; a typical, 40 minute HST observation of the Jovian aurorae spans 230 $\sim 24^{\circ}$ of longitude as the planet rotates. Values in each bin were calculated as the arith-231 metic mean. Figure 1d shows the auroral brightness of the keogram in Figure 1c binned 232 in MLT and ρ_J , with the projected SMO locations corresponding to the first and last 233 exposures included for reference. As Figure 1d represents a ~ 40 min. observation, it 234 effectively spans a single bin in solar CML and can as such be binned in MLT and ρ_e 235 and displayed completely in two dimensions. Emissions mapping to radial distances less 236 than that of SMO originate at lower latitudes than the SMO, as is the case particularly 237 near dusk in Figure 1. The binned distributions of auroral brightness and number of 238 observations per bin are shown in full in Figure 2; to display these distributions, which 239 are binned in three-dimensional, each panel in Figure 2 represents the two-dimensional 240 distribution with respect to MLT and ρ_e corresponding to a single solar CML bin. 241

242

2.2 Galileo PLS Measurements

Plasma parameters derived from the numerical moments of Galileo PLS real-time 243 science data were obtained, as calculated by Frank et al. (2023). The *Galileo* spacecraft's 244 native Inertial Rotor Coordinate (IRC) system, a despun coordinate system based on 245 the spacecraft's geometry, is complex (Bagenal et al., 2016) and has not been fully im-246 plemented into SPICE (Acton et al., 2018), due in part to the Galileo spacecraft her-247 itage predating the SPICE toolkit. SPICE ephemerides for the *Galileo* spacecraft po-248 sition are available for all 6751 moments; spacecraft pointing information is only avail-249 able for 4897 of those 6751. So that the full set of moments can be used, the plasma flow 250



Figure 2. Two-dimensional distributions of the (a,c) auroral brightness and the (b, d) number of observations for both the (a, b) northern and the (c, d) southern hemispheres, with colors for each MLT- ρ_e bin corresponding to the colorbars to the right of each set of panels. Each distribution is labeled with the range of solar CMLs it spans; solar CML ranges for which there are no observations were excluded. In the sample analyzed here, it is evident that the northern hemisphere is typically brighter than the southern and that dusk is typically brighter than dawn.



Figure 3. Plots illustrating *Galileo* PLS coverage of the magnetosphere. Plot (a) shows all 34 *Galileo* orbits projected into Jupiter's equatorial plane in the Jupiter-Despun-Sun (JSS) reference frame, with the region spanning $\pm 30R_J$ in both dimensions highlighted in yellow. (b) A zoomed-in view of the highlighted region in (a), with individual *Galileo* PLS plasma flow speed measurements overplotted as points, colored according to MLT sector: dawn $(03 \le MLT < 09)$ in orange, noon $(09 \le MLT < 15)$ in yellow, dusk $(15 \le MLT < 21)$ in blue, and midnight $(00 \le MLT < 03; 21 \le MLT < 24)$ in purple. (c) A histogram of the number of *Galileo* PLS plasma flow speed measurements in each hour-wide MLT bin. The abundance of dawn and dusk observations, compared to those near noon and particularly near midnight, is evident.

speed is estimated as the root-sum-square of all the velocity components, as the azmiuthal component of the plasma velocity is expected to be much larger than the radial
and polar components.

These numerical moments span 31 of Galileo's 34 orbits, and cover a combined 129 254 days. The plasma parameters span $10R_J \leq \rho_e \leq 30R_J$ within $\sim 1 - 2R_J$ of the equa-255 torial plane, with larger distances from the equatorial plane corresponding to larger ra-256 dial distances. These parameters cover all local times and SIII longitudes, with a bias 257 in local time sampling towards dawn and dusk. Figure 3 illustrates the coverage of the 258 numerical moments relative to *Galileo*'s full orbit and shows this bias. Figures 3a and 259 3b are plotted in the Jupiter-De-Spun-Sun (JSS) reference frame, which is defined to have 260 \hat{Z} aligned with Jupiter's rotational axis, the Sun located in the $\hat{X} - \hat{Z}$ plane, and \hat{Y} com-261 pleting the right-hand orthogonal set. The average plasma corotation rate (R_C) was cal-262 culated for bins spanning 1 hour in MLT and 2 R_J in ρ_e ; as the middle magnetosphere 263 is dominated by magnetic local time effects rather than longitudinal effects (Vogt et al., 264 2011; Ray et al., 2014), the *Galileo* data were not binned by the solar CML of the planet. 265 Binning of the plasma parameters was performed by averaging with weights proportional 266 to the inverse of the parameter variance to be representative of the time-averaged MI-267 coupled system. 268

269 270 The plasma corotation rate R_C is defined as

$$R_C = \frac{v_{flow}}{\rho_e \Omega_J} = \frac{\omega_{flow}}{\Omega_J} \tag{1}$$

where v_{flow} is the calculated linear plasma flow velocity from the *Galileo* PLS data, ω_{flow} is the angular plasma flow velocity ($\omega_{flow} = v_{flow}/\rho_e$), and Ω_J is the angular velocity at which Jupiter rotates ($1.76 \times 10^{-4} \text{ rad s}^{-1}$). R_C is averaged in each bin rather than v_{flow} to account for the expected inverse relationship between equatorial distance ρ_e and v_{flow} . When $v_{flow} = \rho_e \Omega_J$, the plasma is rigidly corotating with the planet and $R_C = 1$. In turn, when $v_{flow} = 0$ then the plasma is fixed with respect to the Sun-



Figure 4. Two-dimensional distributions of the (a) corotation rate (R_C) of the equatorial plasma from *Galileo* PLS moments from Equation 1 and the (b) number of moments. The moments were not binned with respect to solar CML, as the middle magnetosphere is expected to vary primarily in MLT.

Jupiter geometry, or effectively fixed in MLT, and $R_C = 0$. The full set of 6751 plasma parameters used from *Galileo* PLS are summarized in Figure 4, which shows the twodimensional distributions of the corotation rate R_C and the number of moments N with respect to MLT and ρ_e .

281 3 Analysis

The field-aligned current per radian of azimuth, $I_{||}$, in the coupled MI system driving Jupiter's main emission near the ionosphere can be found as

$$I_{||} = -2 \int_{0}^{\rho_{e}} j_{z} \rho_{e}' \, d\rho_{e}' \tag{2}$$

$$=4\Sigma_P^*\Omega_J(1-R_c)F_e\tag{3}$$

adapted from Equation 16 in Cowley and Bunce (2001). Here j_z is the field-aligned cur-282 rent density flowing out of the current sheet lying in the middle magnetosphere's equa-283 torial region, Σ_P^* is the height-integrated effective Pedersen conductance, $\Omega_J = 1.76 \times 10^{-4}$ rad s⁻¹ and R_C are the angular velocity and magnetospheric plasma corotation rates 284 285 defined previously, and F_e is the equatorial flux function, a function which maps the au-286 roral ionosphere to the equatorial middle magnetosphere along contours of constant mag-287 netic flux. The field-aligned current per radian of azimuth $I_{||}$ can be calculated from the 288 auroral brightness observed with HST using Equation 2 and from the plasma flow speed 289 derived from *Galileo* PLS using Equation 3, as will be discussed in Sections 3.1 and 3.2, 290 respectively. 291

3.1 Field-aligned currents from HST observations

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The brightness of the ME aurorae observed with HST is directly proportional to the precipitated energy flux of auroral electrons E_f incident on the atmosphere, with a conversion factor of 10 kR per 1 mW m⁻² (Gustin et al., 2012; Nichols & Cowley, 2022). This energy flux E_f is in turn related to the field-aligned current density just above the auroral ionosphere $j_{||}$ as

$$j_{||} = j_{||,0} \left(\pm \sqrt{2 \frac{E_f}{E_{f,0}}} - 1 \right)$$
(4)

where $j_{\parallel,0}$ is the maximum field-aligned current density above the ionosphere and $E_{f,0}$ 293 is the maximum precipitated energy flux of auroral electrons, both for the case of an ab-294 sence of field-aligned potentials. Equation 4 is derived by assuming the minimum nec-295 essary field-aligned potentials for currents to flow into the ionosphere. The maximum 296 energy flux in the absence of field-aligned potentials is $E_{f,0} = 2N \sqrt{W_{th}/2\pi m_e W_{th}}$ (Equa-297 tion 37 in Cowley and Bunce (2001)), which is a number flux of electrons $(2N\sqrt{W_{th}/2\pi m_e})$ 298 multiplied by a characteristic energy (W_{th}) . $E_{f,0}$ can therefore be estimated by measur-200 able physical parameters; here, $N = 0.018 \text{ cm}^{-3}$ (Bagenal et al., 2016; Huscher et al., 300 2021) and $W_{th} = 5$ keV (Allegrini et al., 2021) are used. Similarly, the maximum field-301 aligned current density just above the ionosphere in the absence of field-aligned poten-302 tials is $j_{\parallel,0} = eN\sqrt{W_{th}/2\pi m_e}$, the number flux of electrons multiplied by e, the ele-303 mentary charge (Equation 28 in Cowley and Bunce (2001)). 304

The quantity j/B is constant along a magnetic field line provided there are no field-305 perpendicular currents intersecting the field line outside of the equatorial and ionospheric 306 regions (Cowley & Bunce, 2001), so $j_{||}$ can be written as $j_z B_i/B_e$, where B_i and B_e are 307 the strengths of the magnetic field along the field line in the ionosphere and the current 308 sheet in the equatorial plane, respectively. The magnetic field strength in the equato-309 rial plane of the magnetosphere B_e , is calculated from the form provided in Vogt et al. 310 (2011), which is itself a fit to in-situ magnetic field measurements from *Pioneer 10*, *Pi*-311 oneer 11, Voyager 1, Voyager 2, Ulysses, and Galileo spanning 20-120R_J. The mag-312 netic field strength in the ionosphere was found using the internal magnetic field model 313 based on Juno's first 33 orbits of Connerney et al. (2022)(henceforth, JRM33), calcu-314 lated to order 13 using the code provided by Wilson et al. (2023), and assuming an al-315 titude of $1R_J$. The magnetic field function of Vogt et al. (2011) is more appropriate for 316 B_e than the more recent JRM33 model as it captures the significant variation of the mid-317 dle and outer magnetosphere with MLT; beyond $10R_{\rm J}$, the higher order terms in the JRM33 318 model become negligible and the resulting field is very nearly dipolar and azimuthally 319 symmetric. 320

Equation 4 can thus be substituted into Equation 2 for j_z to give

$$I_{||} = -2 \int_{0}^{\rho_{e}} j_{||,0} \frac{B_{e}}{B_{i}} \left(\pm \sqrt{2 \frac{E_{f}}{E_{f,0}} - 1} \right) \rho_{e}' \, d\rho_{e}' \tag{5}$$

which can be used to calculate the field-aligned current per radian of azimuth $I_{||}$ cor-321 responding to a given auroral brightness. Evaluation of Equation 5 requires and inte-322 grable auroral electron energy flux $E_f(\rho'_e)$, which in turn requires a function of the au-323 roral brightness over equatorial distance. The variation of the auroral brightness with 324 equatorial distance illustrated in Figure 2 does not represent this function directly. In-325 stead, these distributions show the typical values of the observed ME when the ME maps 326 to a given location in MLT- ρ_e space, which in turn represents the maximum of the field-327 aligned current density j_z for a given span of solar CML. An integrable radial distribu-328 tion of $E_f(\rho'_e)$ is therefore approximated as a Gaussian having a peak value of E_f , a cen-329 ter defined by the corresponding radial bin, and a width defined by the angular width 330 of the ME ($\delta \theta$) magnetospherically mapped to a radial width ($\delta \rho_e$). The resulting ra-331 dial distributions are then numerically integrated from 0 out to the corresponding ρ_e value. 332



Figure 5. Two-dimensional distributions of the integrated field-aligned current per radian of azimuth ($I_{||}$ calculated from Equation 5 for the (a) northern and (b) southern hemispheres, with colors for each MLT- ρ_e bin corresponding to the colorbars to the right. Each distribution is labeled with the range of solar CMLs it covers. Generally, stronger currents are seen to occur at dusk rather than dawn, and when the magnetosphere is more perturbed (i.e., when the ME maps to more distant regions of the magnetosphere).



Figure 6. Two-dimensional distribution of the quantity $I_{||}/\Sigma_P^*$ derived from the *Galileo* PLS moments using Equation 6, with colors in each MLT- ρ_e bin corresponding to the colorbar to the right. Generally, $I_{||}/\Sigma_P^*$ is seen to be smaller at dawn than at dusk.

The resulting values of $I_{||}$ we report are thus average field-aligned currents per radian 333 of azimuth entering the ionosphere at the ME, when the location of the ME maps to the 334 current sheet at the location specified by the corresponding bin. The distributions of $I_{||}$ 335 with MLT, ρ_e , and solar CML in Figure 5 thus illustrate various independent MI cou-336 pling configurations rather than multiple samples of the same configuration. To clarify 337 further, the distributions of $I_{||}$ calculated here are not expected to increase monotoni-338 cally with equatorial distance ρ_e , even though the integral of $F_e(\rho'_e)$ would, for the same 339 reasons that the ME brightness does not increase monotonically with ρ_e in Figure 2. 340

341

3.2 Field-aligned currents from Galileo-PLS data

Returning to Equation 3 and rearranging, the total field-aligned current per radian of azimuth $I_{||}$ flowing into the ionosphere divided by the effective, height-integrated Pedersen conductance Σ_P^* of the ionosphere, can be found as

$$\frac{I_{||}}{\Sigma_P^*} = 4\Omega_J (1 - R_c) F_e \tag{6}$$

The height-integrated effective Pedersen conductance Σ_P^* is the sum of all conductance 342 terms and is reduced from the true value, Σ_P , by a factor of (1-k) to account for the 343 slippage in the ion-neutral coupling in the ionosphere. The values of k range from 0 < 1344 k < 1, with k = 0 corresponding to no slippage of the neutral atmosphere relative to 345 the planet's rigid rotation rate and $k \approx 1$ corresponding to maximal slippage (Huang 346 & Hill, 1989; Nichols & Cowley, 2003). The equatorial flux F_e , which relates locations 347 in the ionosphere to conjugate points in the current sheet in the equatorial plane of the 348 magnetosphere along contours of constant magnetic flux, is a function of both MLT and 349 ρ_e and is calculated using the form provided by Ray et al. (2014). This description of 350 $F_e(MLT, \rho_e)$ is based on a slightly modified version of the empirical magnetic field model 351 used to map HST observations into the equatorial magnetospheric plane (Vogt et al., 2011). 352 The differences between this and the unmodified empirical magnetic field model are great-353 est near the planet; the two descriptions agree throughout the middle magnetosphere where 354 MI coupling currents flow, ensuring consistency between the values derived from *Galileo* 355 PLS and HST observations. 356

The quantity I_{\parallel}/Σ_P^* can thus be solved for using *Galileo* PLS-derived values of the plasma corotation rate R_c and the known form of F_e . This quantity is introduced for convenience and has limited physical meaning, despite having the form of an electric potential. Instead, the quantity $I_{||}/\Sigma_P^*$ groups unknown parameters together, and will allow further exploration of the distribution of Σ_P^* when compared to the values of $I_{||}$ derived from HST observations. Figure 6 shows the distributions of the quantity $I_{||}/\Sigma_P^*$ with MLT and equatorial distance ρ_e .

³⁶⁴ 4 Results and Discussion

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4.1 Azimuthally integrated field-aligned currents

First, we focus on the field-aligned current per radian azimuth $I_{||}$ derived from HST 366 observations, which, unlike the parameter I_{\parallel}/Σ_P^* derived from Galileo measurements, 367 is representative of the field-aligned auroral currents flowing in Jupiter's coupled MI sys-368 tem without any further assumptions about the ionospheric Pedersen conductance. The 369 northern ME is found to have a median current per radian of azimuth of $I_{||} = 9.54^{+11.5}_{-6.35}$ 370 MA rad⁻¹, while the southern ME has a median current per radian of azimuth of $I_{||} =$ 371 $10.6^{+11.1}_{-6.11}$ MA rad⁻¹. These median values are found using a Monte Carlo bootstrap anal-372 ysis with lognormal error perturbation (henceforth just "medians"), in order to better 373 account for the measurement errors in the non-Gaussian distribution of currents (Curran, 374 2014). Upper and lower errors correspond to the 84^{th} and 16^{th} percentiles, respectively, 375 to approximate 1σ errors. These median currents are in very good agreement with the 376 currents calculated from Juno magnetometer measurements, both lying within the $\sim 1-$ 377 27 MA rad⁻¹ range of $I_{||}$ (Nichols & Cowley, 2022) and reproducing the magnitude, af-378 ter accounting for integration over azimuth, and North-South asymmetry previously mea-379 sured (Kotsiaros et al., 2019). 380

4.2 Effective Pedersen conductance

The effective Pedersen conductance (Σ_P^*) can be calculated by dividing the field-382 aligned current per radian of azimuth derived from HST measurements $(I_{||})$ by the quan-383 tity derived from Galileo PLS moments $(I_{\parallel}/\Sigma_P^*)$. Figure 7 shows distributions of this 38/ calculated effective Pedersen conductance for the northern and southern hemispheres; these plots are limited to $10 < \rho_e \leq 30 R_J$ due to the coverage of the Galileo PLS moments. The binned distributions of $I_{||}/\Sigma_P^*$ are assumed to be the same at all solar CML in this 387 analysis. We find 95% of conductances lie in the range $0.03 < \Sigma_P^* < 1.79$ mho in the north 388 with a median of $\Sigma_P^* = 0.14_{-0.09}^{+0.31}$ mho and $0.02 < \Sigma_P^* < 2.26$ mho in the south with a median of $\Sigma_P^* = 0.14_{-0.09}^{+0.34}$ mho, with errors corresponding to the 16th and 84th percentiles. 389 390 These averages are comparable to both theoretical estimates (Millward et al., 2002, 2005) 391 and recent estimates made using Juno ultraviolet spectrograph (UVS) measurements and 392 ionospheric modeling (Gérard et al., 2020, 2021) of $\Sigma_P \approx 0.5$, considering that these 393 reported values are not reduced by the (1 - k) factor. For typical values of $k \approx 0.4$ – 394 0.7 (Millward et al., 2005), the novel method used here to calculate the conductance of 395 the auroral ionosphere is in good agreement with literature values. 396

For clarity, Figure 8 shows the same data as Figure 7, but with the medians and 397 the $84^{th}/16^{th}$ percentile errors of the effective Pedersen conductance in each bin plot-398 ted. By comparison to the average values and errors for each hemisphere overall, the vari-399 ations in conductance with respect to each binning parameter can be seen. Figures 8c 400 and 8f show that Σ_P^* varies minimally with solar CML. Figures 8b and 8e show that the 401 effective Pedersen conductance is generally higher at smaller radial values, correspond-402 ing to higher field-aligned currents when the magnetosphere is in a disturbed enough state 403 for the ME to map to these distances. The conductance thus increases with current, as 404 expected (Nichols & Cowley, 2004). The bin-to-bin variation is greatest when the con-405 ductance is interpreted as a function of MLT, as shown in Figures 8a and 8d. This significant variation in effective conductance with MLT is more likely than the variations 407 with equatorial distance or solar CML to be related to the local time asymmetries in the 408 appearance, distribution, and motion of ME aurorae. Both hemispheres display peaks 409



Figure 7. Two-dimensional distributions of the effective Pedersen conductance Σ_P^* for the (a) northern and (b) southern hemispheres, with the color of each MLT- ρ_e bin corresponding to the colorbars to the right. The effective Pedersen conductance is only calculated where both HST-derived and *Galileo* PLS-derived data are present. Generally, the conductance is greatest at smaller radial distances and nearer dawn.

⁴¹⁰ in the effective conductance between 7-8, 12-13, and 14-15 MLT. It is worth not-⁴¹¹ ing that, without the limb-brightening correction applied to HST-observed auroral bright-⁴¹² ness, derived field-aligned currents would be increased more near dawn and dusk than ⁴¹³ near noon, and Σ_P^* would increase proportionally. The overestimation of the limb-brightening ⁴¹⁴ correction factors thus results in an underestimation of the conductance near the planet's ⁴¹⁵ limbs at dawn and dusk, and a more accurate model of Jupiter's limb-brightening would ⁴¹⁶ heighten the peak in Σ_P^* between 7-8 MLT further than the others.

Figure 9 shows the complete conductance distributions mapped onto Jupiter's au-417 roral ionosphere for each solar CML bin, allowing the variation in Σ_P^* with local time 418 and location relative to the SMO to be visualized. The generally increased effective Ped-419 ersen conductance near local dawn, located to the left of each frame in Figure 9, is ev-420 ident. The smooth decrease in Σ_P^* with increasing ρ_e can be seen as a decrease in Σ_P^* 421 with increasing latitude, particularly in the noon and dusk sectors, in Figure 9a. The 422 same trend is not seen in Figure 9b, as the middle magnetosphere maps to a smaller range 423 of latitudes in the southern ME than in the northern ME. 424

From the derived distributions of Σ_P^* alone, we cannot determine the cause of the variation of the conductance with MLT. It is of interest, however, that the effective Pedersen conductance peaks in the late-dawn (7 - 8 MLT) and noon (12 - 13 MLT) regions are generally colocated with known subcorotating emission features within the ME: the dawn storms and associated, less bright subcorotating emission features in the post-



Figure 8. Plots showing the trends in the median effective Pedersen conductance Σ_P^* with MLT (a, d), ρ_e (b, e), and solar CML (c, f) for the northern (a, b, c; blue circles) and southern (d, e, f; red triangles) hemisphere ME. The conductance varies widely with MLT and insignificantly with solar CML.

dawn region (Rutala et al., 2022) and the noon discontinuity and auroral spot near noon
(Radioti et al., 2008; Palmaerts et al., 2014).

The co-occurrence of increased ionospheric conductance and subcorotating auro-432 ral features within the ME was hypothesized by Rutala et al. (2022) as an explanation 433 of subcorotational behavior near dawn. The basic premise is that, if the ionospheric con-434 ductance is locally increased for a reason unrelated to MI-coupling currents, the MI-coupling 435 currents will increase in magnitude due to the heightened conductance, accelerating mag-436 netospheric plasma up to the corotation rate of the planet; as the magnetosphere gen-437 erally compresses from dawn through noon, the linear velocity of the recently-accelerated 438 magnetospheric plasma would exceed the local angular corotational velocity as the sys-439 tem rotates, thus reducing or reversing the field-aligned currents. In the ionosphere, this 440 would appear as a bright auroral form associated with the increased currents which ends 441 abruptly as the currents reverse, thus appearing fixed in local time. This picture meshes 442 well with the noon ME discontinuity observed by Radioti et al. (2008), which is expected 443 to be associated with reduced or reversed field-aligned currents. The secondary peak in 444 Σ_{P}^{*} near noon may be associated with the subcorotational noon auroral spot (Palmaerts 445 et al., 2014), as following noon the magnetosphere expands again, thus requiring increased 446 field-aligned currents to bring plasma up to local corotational velocity. 447

This second peak in Σ_P^* near 12 MLT may instead be caused by increased field-448 aligned currents caused by shearing motions of magnetospheric plasma, as modeled by 449 Chané et al. (2018). Generally, as an increase in the field-aligned currents will cause an 450 increase in the effective Pedersen conductance, we cannot distinguish between cause and 451 effect with this data set: high currents could cause increased conductance, or heightened 452 conductance may drive increased currents. It is of note that the conductance distribu-453 tions found in Figure 8 are more similar to the modeled conductance distribution in LT 454 found by Tao et al. (2010) than to the distributions in solar CML found by Gérard et 455 al. (2020, 2021). In the latter case, the differences may in part be explained by the dif-456 ference in observational integration time. Images from HST span non-overlapping 30-457 100 s exposures while spectral images from Juno were integrated over 20-50 min (Gérard 458 et al., 2020, 2021), which would introduce more smoothing into the Juno UVS based maps 459 than is present in this analysis. The similarity in form between the Σ_P^* distributions found 460 here and those of Tao et al. (2010) may indicate a relationship between heightened dawn 461



Figure 9. Polar, orthographic views of Jupiter's north auroral region, with the derived Σ_P^* distributions shown mapped onto the planet by mapping MLT and ρ_e onto λ_{III} and ϕ . Each frame corresponds to one solar CML bin with the mean solar CML, and hence noon local time, located at the bottom of the image. The SMO is shown by a red-dashed line, and λ_{III} and ϕ graticules are shown in yellow. Values of Σ_P^* have been log-scaled and correspond to the colorbar to the right. The increased conductance near dawn, toward the left side of each frame, can be seen, as can the increased conductance at lower latitudes (mapping to smaller ρ_e).

sector conductance and incident solar extreme ultraviolet (EUV) photons, which increase
 the Pedersen conductance by ionizing the ionosphere.

464 5 Conclusions

We have outlined a novel method for deriving values of the effective Pedersen con-465 ductance Σ_{P}^{*} of Jupiter's ME auroral ionosphere by combining remote observations of 466 the Jovian ME and in-situ observations of the angular velocity, or corotation rate, of mid-467 dle magnetospheric plasma. This method has been developed from the theoretical un-468 derstanding of MI coupling at Jupiter, which links the field-aligned currents entering the 469 ionosphere, estimated from the auroral brightness measured with HST, to the motion 470 of middle magnetospheric plasma, calculated by moment analysis of *Galileo* PLS mea-471 surements. Equivalent regions of the auroral ionosphere and equatorial magnetosphere 472 are found using magnetic flux equivalence mapping. The non-overlapping 288 HST ob-473 servations and 6751 Galileo measurements used in this analysis are taken to be repre-474 sentative of the time-averaged Jupiter system. 475

From the HST observations, we find field-aligned currents entering the ionosphere 476 of $I_{||} = 9.54^{+11.5}_{-6.35}$ MA rad⁻¹ and $I_{||} = 10.6^{+11.1}_{-6.11}$ MA rad⁻¹, corresponding to the northern and southern ME, respectively, in agreement with recent Juno-based measurements 477 478 (Kotsiaros et al., 2019; Nichols & Cowley, 2022) and theoretical estimates (Hill, 2001; 479 Cowley & Bunce, 2001). Combining these values with the parameter $I_{\parallel}/\Sigma_{P}^{*}$ derived from 480 in-situ Galileo PLS measurements, we find the effective Pedersen conductance Σ_P^* , re-481 duced from the true Pedersen conductance by a factor of $1 - k \approx 0.5$. Σ_P^* ranges be-482 tween $0.03 < \Sigma_P^* < 1.79$ mho in the north and $0.02 < \Sigma_P^* < 2.26$ mho in the south, with typical values of $\Sigma_P^* = 0.14^{+0.31}_{-0.08}$ mho and $\Sigma_P^* = 0.14^{+0.34}_{-0.09}$ mho in the northern and 483 484 southern ME, respectively. These typical values are consistent with theoretical and modeled values (Millward et al., 2002, 2005; Gérard et al., 2020, 2021), but the distributions 486 of Σ_P^* we find reveal that it varies primarily in MLT, rather than solar CML. This anal-487 ysis indicates that the field-aligned currents derived from MI coupling theory, which have 488 historically been used to explain Jupiter's ME, adequately describe the relationship be-489 tween ME auroral brightness and the motion of middle magnetospheric plasma. Further, 490 the heightened effective Pedersen conductance near MLTs of 07-08 and 12-13 MLT 491 we find are approximately co-located with auroral features in the ME with subcorota-492 tional motions (Rutala et al., 2022; Radioti et al., 2008; Palmaerts et al., 2014). The re-493 sults we present are compatible with the theory that solar EUV ionization of the auro-494 ral ionosphere is key to controlling the motions of subcorotational auroral features in the 495 dawn sector. We cannot, however, distinguish between this case and the case of otherwise-496 increased dawn currents causing locally elevated conductances. Breaking the observa-497 tional degeneracy between these cases should be done with comparisons of the distribu-498 tions found here to models of the field-aligned currents flowing in the MI coupling sys-499 tem under varying ionospheric conductance conditions. 500

Open Research 501

All Hubble Space Telescope observations used in this analysis are available at the 502 Mikulski Archive for Space Telescopes hosted by the Space Telescope Science Institute. 503 and have been collected into a single dataset for ease of access (Rutala, 2022). All Galileo 504 PLS real-time-science data are available through the Planetary Plasma Interaction (PPI) 505 node of the Planetary Data System (PDS) (Frank et al., 2023). This research made use 506 of the ionosphere-magnetosphere mapping code of Vogt et al. (2011) and the internal mag-507 netic field model of Connerney et al. (2022) as made available by Wilson et al. (2023) 508 509 to allow comparison between in-situ and remote measurements.

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